TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

EETU SIITAMA

TECHNICAL PERFORMANCE ASSESSMENT AND QUALITY CONTROL OF ULTRASOUND DEVICE MONITORS

Master of Science Thesis

Examiner: Professor Hannu Eskola

The examiner and topic of the thesis
were approved on 31 October 2018

ABSTRACT

EETU SIITAMA: Technical performance assessment and quality control of ultrasound device monitors
Tampere University of Technology
Master of Science Thesis, 52 pages, 6 Appendix pages
December 2018
Master's Degree Programme in Science and Engineering
Major: Advanced Engineering Physics
Examiner: Professor Hannu Eskola

Keywords: ultrasound, medical display, quality control, AAPM, DICOM, GSDF

The purpose of this study was to investigate and evaluate the current technical performance of ultrasound imaging device displays in the Hospital District of South Ostrobothnia and in Pirkanmaa Hospital District. Ultrasound device monitors are used in diagnostics as the interpretation of the image is generally done simultaneously while the doctors perform the examination. There are certain recommendations about the technical performance of these kinds of diagnostic displays, but they are not generally applied to ultrasound devices.

The performance of the displays was evaluated with tests and test patterns developed by a task group set by the American Association of Physicist in Medicine (AAPM). Only certain tests were chosen to be conducted as the protocol would otherwise become too heavy while the benefit from additional information would have been minimal. The focus of the study was on luminance measurements and the measurement of illuminance.

The results show that the technical performance of most of the displays are not sufficient. The lifetime of the ultrasound machine surpasses the lifetime of the display, but nothing is currently done as there is no proper quality assurance protocol. The lack of proper quality assurance protocol is due to the fact that no legislation or regulations require it as non-ionizing radiation is used. This means that the quality of ultrasound imaging devices depends mainly on the physicists and maintenance engineers working in the hospitals.

The singular most important technical performance parameter is the maximum luminance of the display. Although the luminance responses were evaluated against the greyscale standard display function (GSDF), it is questionable if GSDF compliance should be required from ultrasound device displays. Based on this research the measurement of the maximum luminance should be executed at least annually. The measurement procedure is easy, and it can be taught to any of the staff members and it can tell a lot about the condition of the display. It is also suggested that the hospitals should find out the cost of changing the display and thus probably prolonging the lifetime of the whole machine.

TIIVISTELMÄ

EETU SIITAMA: Ultraäänilaitteiden näyttöjen teknisen suorituskyvyn arviointi sekä laadunvalvonta
Tampereen teknillinen yliopisto
Diplomityö, 52 sivua, 6 liitesivua
Joulukuu 2018
Teknis-luonnontieteellinen diplomi-insinöörin tutkinto-ohjelma
Pääaine: Teknillinen fysiikka
Tarkastaja: Professori Hannu Eskola

Avainsanat: ultraääni, radiologinen näyttö, laadunvalvonta, AAPM, DICOM, GSDF

Tämän tutkimuksen tarkoituksena oli tutkia ja arvioida tämänhetkisten ultraäänilaitteiden näyttöjen suorituskykyä Etelä-Pohjanmaan sairaanhoitopiirissä sekä Pirkanmaan sairaanhoitopiirissä. Ultraäänilaitteiden näyttöjä käytetään diagnostiikassa, koska lääkärit tekevät diagnoosin yleensä samanaikaisesti kuvausta suorittaessa. Tällaisille diagnostisille näytöille on annettu tiettyjä suosituksia teknisen suorituskyvyn osalta, mutta niitä ei tavallisesti sovelleta ultraäänilaitteisiin.

Näyttöjen suorituskykyä arvioitiin American Association of Physicists:n asettaman työryhmän kehittämien testien ja testikuvien avulla. Vain osa suositelluista testeistä valittiin suoritettavaksi, koska lisäinformaatio olisi muuten ollut liian pieni suoritettuun työmäärään suhteen. Näissä tutkimuksissa painopiste oli eri luminanssien ja illuminanssin mittauksissa.

Tulokset osoittavat, että läheskään kaikkien näyttöjen tekninen suorituskyky ei ole riittävä. Koko laitteen käyttöikä on yleensä pidempi kuin näytön käyttöikä, mutta tällä hetkellä asiaan ei juuri reagoida, koska sopivia laadunvarmistusprotokollia ei ole. Tämä johtuu siitä, että lainsäädännössä tai ohjeistuksissa ei vaadita laadunvarmistusohjelmaa, mikäli laite käyttää ionisoimatonta säteilyä. Näin ollen vastuu laitteiden kunnosta on pääsääntöisesti sairaalafyysikoilla ja -insinööreillä.

Tärkein yksittäinen teknisen suorituskyvyn parametri on näytön maksimiluminanssi. Vaikka luminanssivastetta verrattiin Grayscale Standard Display Functioniin (GSDF), on silti kyseenalaista tulisiko ultraäänilaitteiden näytöiltä vaatia GSDF:n noudattamista. Tutkimustulosten perusteella näyttöjen maksimiluminanssi tulisi mitata vähintään kerran vuodessa. Mittaus on helppoa, se voidaan opettaa kenelle tahansa henkilökunnasta ja siitä saatava tieto kertoo paljon näytön suorituskyvystä. Lisäksi suositellaan, että sairaalat ottaisivat selvää siitä, kuinka paljon näytön vaihdot kustantaisivat, sillä ne voisivat parhaimmillaan pidentää koko laitteen käyttöikää.

PREFACE

I am very grateful for my supervisor professor Hannu Eskola who provided me this topic. It has proven to be more interesting than I first tought. This opportunity been really educating in many ways and it has made it possible for me to take several steps on my journey of becoming a medical physicist.

I would like to thank chief physicist of radiology Jyrki Ruohonen for welcoming me warmly and guiding me while I worked in Seinäjoki.

Almost last but definitely not least, a special thanks to specialising physicist Anna Vuorenmaa and physicist Ullamari Hakulinen who have both guided me and made the taking of the next step easier for me. I've actually had some fun working on this project, thanks to great co-workers, and I am really grateful that I have been able to participate on different projects and seen many things in the hospital. Even though, they were not always directly related to this thesis.

It has been an amazing journey and I have changed my mind countless times during it, but luckily for the last few years I have had (almost) clear goal in my mind. There is still quite a long way to go but I am getting closer with every step I take. The voyage from studying civil engineering in Tampere University of Applied Sciences through University of Turku to here, Tampere University of Technology, has been full of adventures and experiences I never could have imagined.

Hard work has played a part in all of this but the courage to jump into unknown, pure luck and amazing friends have played at least an equally large role. I would like to express my gratitude to my dear friends: the Boys and the rest of the 2015 board of Delta ry. I might have left Turku, but Turku will never completely leave from me.

In Tampere, Finland, on 14 November 2018

Eetu Siitama

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
ACR	American College of Radiology
CIE	fr. Commission Internationale d'Éclairage, International Commission on Illumination
CRT	Cathode Ray Tube
DICOM	Digital Imaging and Communications in Medicine
GSDF	Grayscale Standard Display Function
IPS	In-Plane Switching
JND	Just-noticeable Difference
LCD	Liquid Crystal Display
NEMA	National Electrical Manufacturers Association
OLED	Organic Light Emitting Diode
PACS	Picture Archiving and Communication System
SIIM	Society for Imaging Informatics in Medicine
ST Guides	fi. Säteilyturvallisuusohjeet, Regulatory Guides on radiation safety
STUK	fi. Säteilyturvakeskus, Finnish Nuclear and Radiation Safety Authority
TFT	Thin Film Transistor
TG	Task Group
TN	Twisted Nematic

CR	contrast ratio
E	irradiance (in chapter 2), illuminance (in other chapters)
E_v	illuminance (in chapter 2)
$j(L)$	JND index of luminance value L
J_i	JND index corresponding to the test pattern TG18-LN-8-i
J_{max}	maximum value of JND index
J_{min}	minimum value of JND index
L	radiance (in chapter 2), luminance (in other chapters)
L_{amb}	measured ambient luminance reflected from the display
L_{max}	measured maximum luminance
L'_{max}	observed maximum luminance
L_{min}	measured minimum luminance
L'_{min}	observed minimum luminance
$L(p)$	measured luminance with input value p
$L'(p)$	observed luminance with input value p
L_v	luminance (in chapter 2)
λ	wavelength
LR'	luminance ratio
Ω, ω	solid angle
P_i	grayscale value corresponding to the test pattern TG18-LN-8-i
ΔP	change in greyscale value in the measurement range
Φ	radiant flux
Φ_v	luminous flux
Q	radiant energy
R_d	diffusive reflection coefficient
R_s	specular reflection coefficient
s	area of projection
s_0	surface area
t	time
θ	projection angle
$V(\lambda)$	photopic luminosity function
$V'(\lambda)$	scotopic luminosity function

1. INTRODUCTION

Ultrasound imaging is the second most widely used imaging modality in health care after x-ray imaging. In Finland over 6 million x-ray examinations and approximately 660 000 ultrasound examinations are performed every year (the numbers are 3 years old). Ultrasound imaging is used as a complementary studies or if possible instead of x-ray imaging and the number of examinations grows every year as the technology develops. Ultrasound is preferred over x-ray imaging as it uses mechanical waves instead of ionizing radiation as there is no scientific evidence of connection between exposure to mechanical waves used in ultrasound imaging and cancer. [38, 39]

The quality control in medical imaging is extremely important as it ensures that the used equipment is in the best possible condition. If the devices are faulty or otherwise in poor condition, in worst case scenario, this could lead to weakened or wrong diagnostics. As ultrasound uses non-ionizing radiation, the quality assurance of this imaging modality is quite non existent at the moment but it has started to develop. In every imaging modality the display is the last piece of the whole imaging chain and as the chain is only as strong as its weakest link there is no sense in using state of the art technology and devices to acquire the data if the final representation of it is poor.

Extensive studies about the display quality and its effects on diagnostics have been done in different uses of x-ray imaging [8, 21] but ultrasound imaging has been nearly forgotten. The display quality in different imaging modalities have been studied quite recently (2016) by Silosky *et al.* [34] but only one study concentrating in ultrasound imaging by Moore *et al.* was found [26]. The study done by Moore *et al.* is currently about 7 years old and their methods had some limitations so it is also scientifically relevant to investigate the state of the ultrasound imaging device displays used in hospitals and health centres. Also, the display technologies have developed and advanced in these years so it is presumable that the findings could be different.

The goal of this study is to evaluate the condition and technical performance of ultrasound device displays in the Hospital District of South Ostrobothnia and Pirkanmaa Hospital District and to ponder what kind of protocols could be implemented in the hospitals to monitor the quality of ultrasound device displays.

The thesis is divided into 9 different chapters. First in chapter 2 the basic physical quantities related to the measurements are defined. It is important to start from the basics as strong background in any subject is the foundation of deeper understanding. Chapter 3 introduces the monitor technologies that are currently in wide use, especially in medical displays, and also the incoming technology. Also, the classification of medical displays will be

discussed.

Standards and recommendations in the field will be presented in chapter 4. International recommendations and practices will be discussed and in the end we will take a look into the Finnish legislation and the lack of it when considering medical displays. The measured quantities and their reference values acquired from the previously discussed recommendations are discussed in chapter 5 and the measurements of these parameters are discussed more thoroughly in chapter 6.

Lastly, the measurement results are presented in chapter 7 and they will be discussed separately in chapter 8 along with the possible outcomes and suggestions for further actions. In the end everything is tied up together in chapter 9 and some additional figures and the largest tables where the results have been gathered collectively are presented in the appendix A

2. RADIOMETRY AND PHOTOMETRY

In the following chapter, the basics of radiometry and photometry will be discussed and the measured photometric quantities will be defined through their radiometric counterparts. The measured photometric quantities are illuminance, E_v, and luminance, L_v and their corresponding radiometric quantities are irradiance, E and radiance, L. The subscript v means "vision" or "visual" and it is used to distinguish the photometric quantities from radiometric ones. [25]

Radiation is the propagation of energy through space in different kinds of forms, mass or particles. In general, radiometry is the science of radiation which includes for example measurements, units, terminology and its interaction with matter. Usually radiometry is considered to be the science of optical electromagnetic radiation which includes ultraviolet, visible and infrared radiation. Photometry can be thought as a branch of radiometry and it is the same for visible light as radiometry is for the whole optical spectrum.

2.1 Radiometric quantities

To define irradiance and radiance, few other quantities needs to be defined first. Radiant energy Q is the energy ($[Q] = \mathrm{J}$) which is emitted, absorbed or propagating through a specified surface with a certain area in the given time.

Radiant flux (Φ) is the flow rate of radiant energy ($[\Phi] = \mathrm{W}$) and it is defined

$$\Phi = \frac{dQ}{dt}. \tag{2.1}$$

All quantities can be defined generally or for a specific wavelength as if we would be dealing with monochromatic radiation. When a specific wavelength is considered a subscript λ is used. This definition holds for any spectral quantities and the definition for example spectral radiant flux would be

$$\Phi_\lambda = \frac{d\Phi}{d\lambda}. \tag{2.2}$$

Irradiance, E, is the radiant flux per unit area ($[E] = \frac{\mathrm{W}}{\mathrm{m}^2}$) in the specified surface. Irradiance is not angle depended so every direction from the hemisphere above or below the point must be included (figure 2.1). Definition of irradiance is

$$E = \frac{d\Phi}{ds_0}, \tag{2.3}$$

where ds_0 is an element of the surface area.

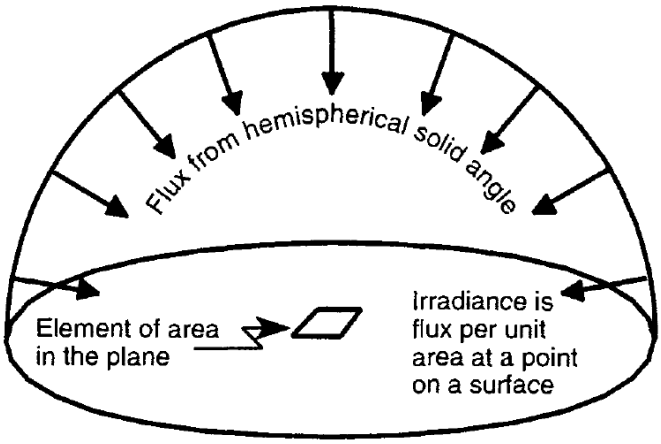

Figure 2.1. *Illustration of the irradiance definition. [25]*

As radiance is direction depended, a three dimensional analog for two dimensional angle is needed to be able to define radiance. This quantity is called solid angle which is usually marked with Ω and its unit is steradians (sr). Solid angle is defined by a point and a closed curve in space. The size of the solid angle is the projection area of the closed curve on a unit sphere surface.

Now, radiance, L, is the radiant flux per unit area and solid angle ($[L] = \frac{\mathrm{W}}{\mathrm{sr} \cdot \mathrm{m}^2}$) and its defined

$$L = \frac{d^2\Phi}{d\omega\, ds} = \frac{d^2\Phi}{d\omega\, ds_0\, cos\, \theta}, \tag{2.4}$$

where $d\omega$ is the element of solid angle, $ds = ds_0\, cos\, \theta$ is the area of the projection of the elemental area ds_0 in the surface, and θ is the angle between the element of flux and the specific point on the surface (figure 2.2).

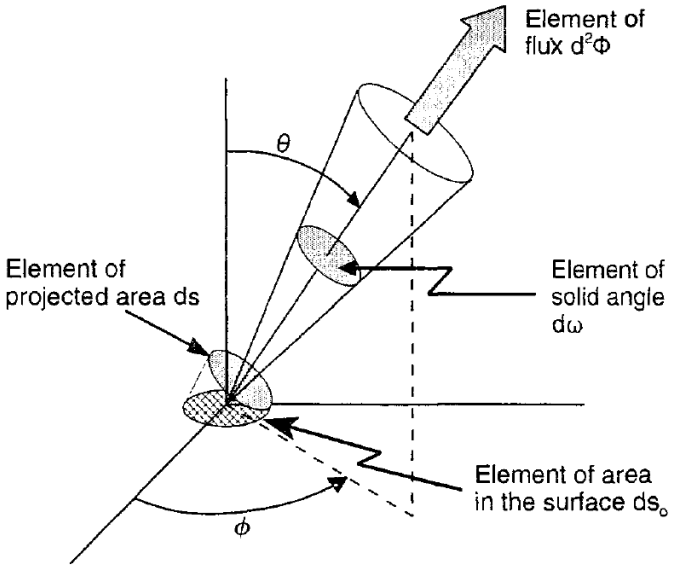

Figure 2.2. *Illustration of the radiance definition. [25]*

As irradiance E is the sum of all radiances L over a finite non-zero solid angle Ω, they have a fundamental relationship

$$E = \int_{\Omega} L(\theta, \phi) \cos\theta \, d\omega. \tag{2.5}$$

2.2 Photometric quantities

Human eye responds only to electromagnetic radiation which has wavelengths approximately from 360 to 800 nm. This is called visible light or in some references just "light".

In the eye, and more specifically in the retina, light is directly sensed by two types of photoreceptor cells: rods and cones. Rods function mainly in dim lighting when the illumination is weak. They provide the black-and-white vision and rod vision is also known as scotopic vision. Humans usually have three kinds of cone cells, which each are sensitive to different wavelengths of visible light. So the cones are primarily responsible for perception of colours and day vision. Cone vision is also known as photopic vision.

Due to the fact that human eye is more sensitive to some colours or wavelengths than others the International Commission on Illumination, the abbreviation CIE comes from its French name Commission Internationale de l'Éclairage, standardised the photopic spectral response of human observer in 1924. In 1951 CIE adopted the standard scotopic luminosity function $V'(\lambda)$ [12] and the standard photopic luminosity function $V(\lambda)$ was last updated in 2007 [11]. Both luminosity functions are presented in the figure 2.3.

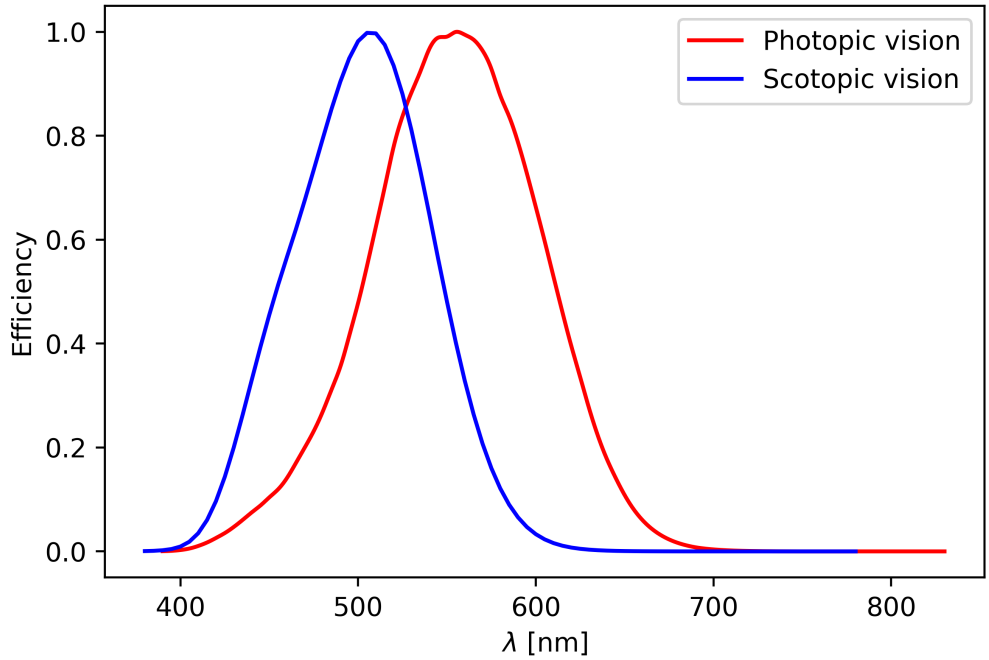

Figure 2.3. *Spectral luminous efficiency functions for photopic and scotopic vision. [40]*

Now we have everything needed to define the analogous photometric quantities, equations (2.6) - (2.8), for the previously defined radiometric quantities.

$$\Phi_v = 683 \frac{\text{lm}}{\text{W}} \int_\lambda \Phi_\lambda V(\lambda) d\lambda, \qquad [\Phi_v] = \text{lm} \tag{2.6}$$

$$E_v = 683 \frac{\text{lm}}{\text{W}} \int_\lambda E_\lambda V(\lambda) d\lambda, \qquad [E_v] = \frac{\text{lm}}{\text{m}^2} = \text{lx} \tag{2.7}$$

$$L_v = 683 \frac{\text{lm}}{\text{W}} \int_\lambda L_\lambda V(\lambda) d\lambda, \qquad [E_v] = \frac{\text{lm}}{\text{sr} \cdot \text{m}^2} = \frac{\text{cd}}{\text{m}^2} \tag{2.8}$$

As the luminosity functions only give relative spectral response a conversion factor (683 lm/W) is used to convert the quantities to absolute values. This conversion factor comes directly from the definition of candela.

3. MONITOR DISPLAY TECHNOLOGIES AND CLASSIFICATION

Cathode rays were discovered in 1850's and the first cathode ray tube (CRT) oscilloscope was invented in 1897. The commercialisation of CRT monitors began in the 1920's, and it started the triumph of CRT display technology which lasted for over 80 years. The decline began in 2000's and liquid crystal displays (LCD) superseded CRTs at the end of the decade.

As CRT monitors have practically ceased to exist in ultrasound devices, they will not be discussed further. Instead the focus will be on currently used liquid crystal displays (LCD) and emerging organic light-emitting diode (OLED) displays which could supersede LCDs in the future. Also, the classification of medical displays will be discussed at the end of the chapter.

3.1 Liquid crystal displays

Liquid crystals were discovered in 1888 but it took 80 years before their applications in displays. The invention of LCDs enabled portable electronics due to their small size.

Liquid crystallinity is a state of matter, just like solid or gas, in which the order of molecules is somewhere between the full long-range positional order of crystals and complete positional disorder of liquids. The least ordered and simplest phase of liquid crystallinity is the nematic phase. In this phase the rod-shaped molecules, which are used in display technology, have only orientational order but positions of the molecules are random. [20] The transition from isotropic to nematic phase is illustrated in the figure 3.1.

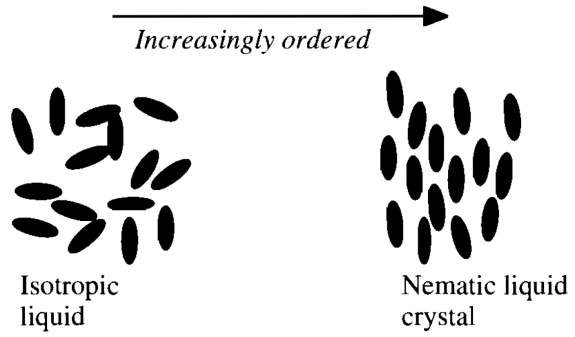

Figure 3.1. *The phase transition from isotropic to nematic phase. [20]*

Usually the molecules that form a nematic phase have a permanent electric dipole. Without an applied field, the probability that the dipole points in either direction is equal. The orientation of the molecules can be easily changed by applying electric or magnetic fields. The aligning of the molecules gives rise to the optical properties of liquid crystals that are crucial for the display technology. Especially the ability to affect the polarisation of light. [20]

Nowadays practically all monitors are active matrix displays. This means that the voltage applied to each singular pixel is controlled by a separate thin film transistors (TFT) and capacitors as every pixel is made of three coloured sub-pixels: red, green and blue. The colours are produced by using colour filters. Every pixel receives a pulse in horizontal and vertical direction which guides the voltage over the capacitor and isolates the pixel from others so that pixels will not affect each other. [16]

The most important structures in the brightness of liquid crystal displays are the light source or backlight, bottom and top polarisers, and the actual liquid crystal phase. These are presented in figure 3.2.

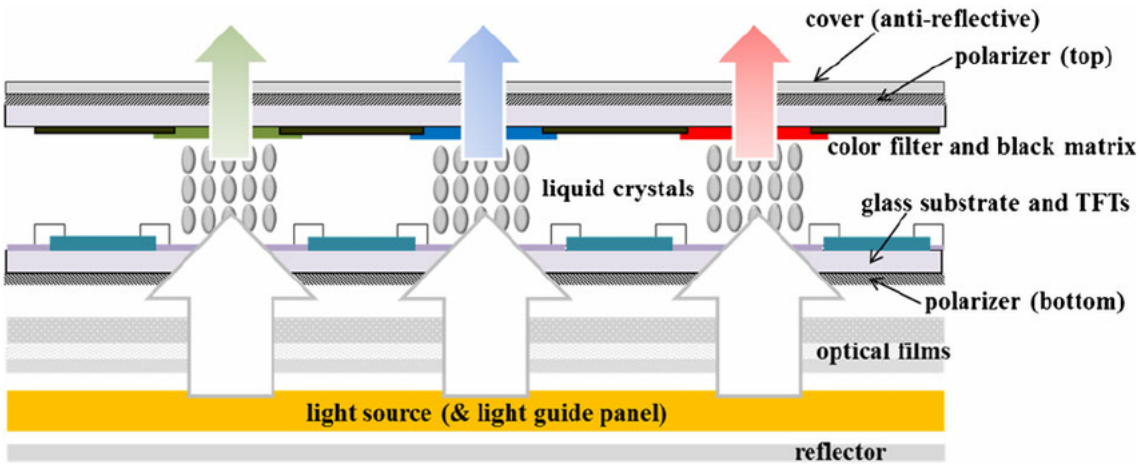

Figure 3.2. *The typical simplified structure of liquid crystal display. [28]*

The basic idea is that the polarising axes of the two polarisers are perpendicular to each other. So, if there was nothing else between them all none of the light would be passed through. The liquid crystal phase is between these two polarisers and it affects the polarisation of the light. When voltage is applied the alignment of the molecules changes and different amount of light passes through the last polariser as the polarisation of the propagating light is changed in the liquid crystal phase.

How the applying of voltage affects the alignment of liquid crystal molecules and the amount of light that is passed depends on the panel type. The most common panel types used nowadays are twisted nematic (TN) and in-plane switching (IPS) and the technologies are discussed in more detail below.

3.1.1 Twisted nematic

In twisted nematic displays two alignment plates are used to orientate the rod-shaped molecules. The molecules are aligned parallel to the polarisers near the both polarisers and the angle of the molecules changes in planes between the plates in a continuous manner. When the voltage is applied to the pixel, depending on the amplitude, the molecules start to turn perpendicular to the plate surfaces. When the voltage is off the molecules change the polarisation of the propagating light and none of the light is filtered. At maximum voltage the molecules align parallel to the applied electric field and the do not affect the polarisation of light, so all of it is filtered. The operating principle of twisted nematic panel is also visualised in figure 3.3. [6, 16, 20]

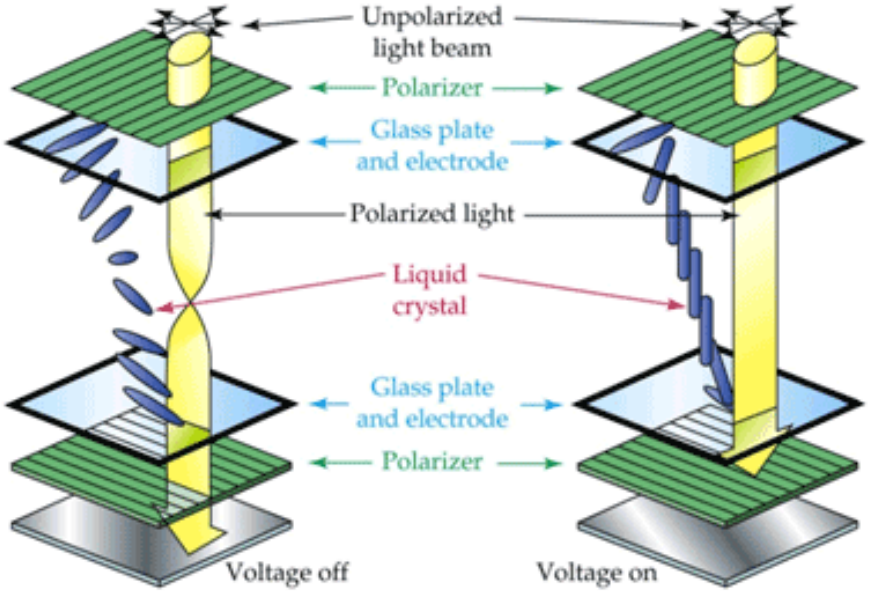

Figure 3.3. *Twisted nematic panel operating principle. Modified from [30]*

3.1.2 In-plane switching

In in-plane switching the electrodes that create the electric field are on the same side when in twisted nematic they are on different sides of the liquid crystal phase (see figure 3.3). This means that the electric field is perpendicular to the plates. As in twisted nematic the polarisers' axes are perpendicular to each other but the molecules are not twisted along the way. Instead, they are aligned so that they are parallel to the transmission axis of the other polariser. This way the, when the voltage is off, the molecules will not change the polarisation of light and everything is filtered on the later polariser. As the voltage is applied, the molecules twist on the planes so that they will change the polarization of light. [6, 10, 18]

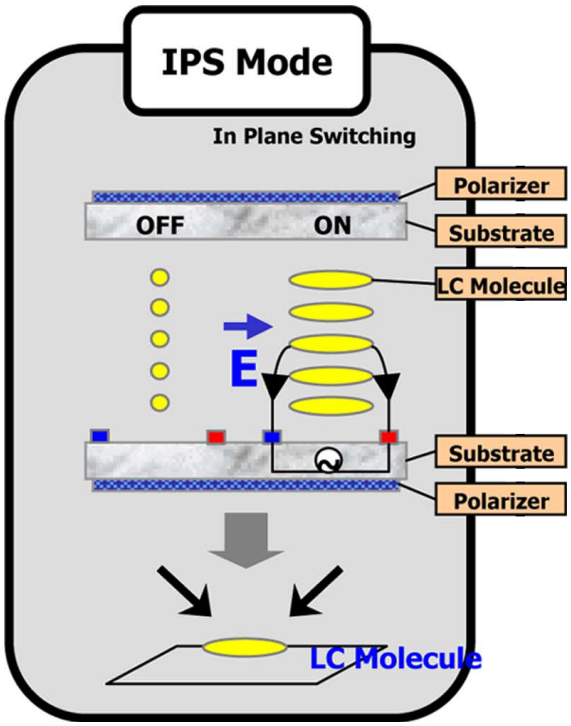

Figure 3.4. *In-plane switching panel operating principle. Modified from [18]*

3.2 Organic light emitting diode displays

The OLED displays are based on organic molecules that have electroluminescent properties. This means that they emit light when electric current passes through them or electric field is applied. In contrast to LCDs the OLED displays do not need a separate backlight as every pixel is light source itself. As every pixel works as a light source, they can be completely turned off and there will be no "leaking" light so the contrast in OLED displays is better than in LCDs. The independency of every pixel can also be disadvantage. If certain pixels or colours are regularly used, they can dim more than other pixels and thus make the brightness of images uneven. [22]

The structure of OLED display is presented in figure 3.5. As can be seen, OLEDs are constructed from different layers. Typically the structure is two layers of organic materials between two electrodes, anode and cathode. The other one of the organic material is conductive and the other one is emitting. The materials work basically as organic semiconductors. When the voltage is applied, electrons move from the emitting layer to the conductive layer and thus create positively charged holes to the emitting layer. As the hole and electron recombine later, light is emitted. The wavelength of the light depends on the organic materials that are used.

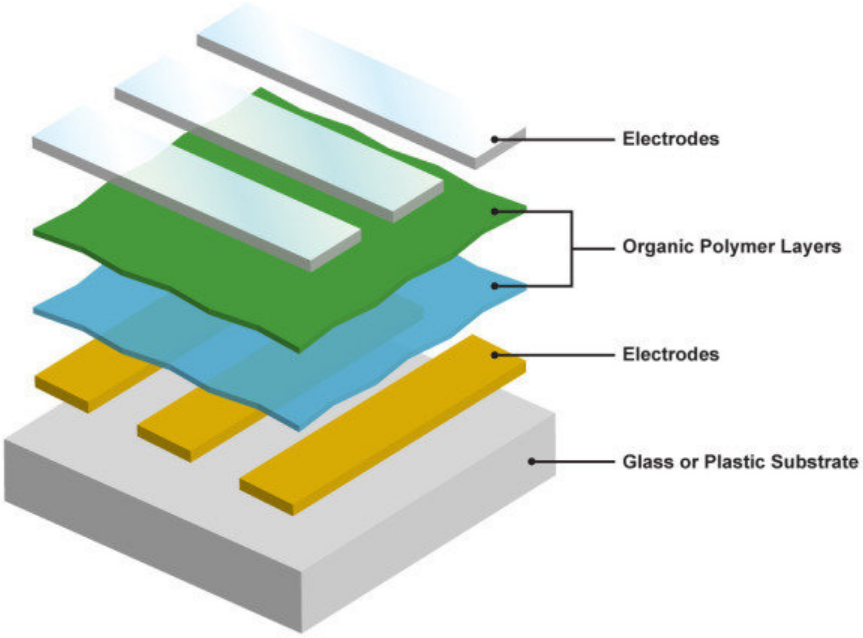

Figure 3.5. *Basic structure of OLED display. [13]*

3.3 Medical display classifications

Displays used in medical imaging modalities can be classified as primary or secondary displays. Primary displays are displays that are used in diagnostic purposes or otherwise primary interpretation of medical images. Primary displays are typically used in radiology in separate room where medical images are interpreted. Secondary displays are used for other purposes than providing the original diagnostic interpretation. This includes later review of images and the displays that are used to verify the quality of images while performing the actual imaging. Both of these types have some technical specifications that they should fulfil. [4, 36]

Primary displays are widely used while interpreting x-ray and magnetic resonance images but ultrasound images are rarely saved for later use. In ultrasound imaging doctors themselves are performing the imaging procedure and they usually interpret the images on the go. As the display is integrated and used while acquiring the medical images it might be classified as a secondary display. As the diagnostics are usually performed at the same time as imaging the displays should however be classified as primary displays. This makes the ultrasound imaging device displays fall in-between these two classifications and there are no clear recommendations which one it should be. Although, it is clear that they should at least fulfil the requirements for secondary displays.

4. STANDARDS AND RECOMMENDATIONS

There are no standards for the quality control of the radiological displays. Some organizations have tried to unify the displaying of medical images and the quality control of the displays itself. In this chapter the worldwide most generally accepted recommendations are discussed along with requirements and recommendations of Finnish legislation and authorities. Even though in most cases the standards and recommendations are meant for displays used in x-ray imaging, they are applied also to ultrasound as there are no other recommendations currently.

4.1 Digital Imaging and Communications in Medicine

As the digital imaging modalities were introduced and they started to increase, along with computers, in diagnostics the American College of Radiology (ACR) and National Electrical Manufacturers Association (NEMA) joined forces and formed a committee to standardise imaging and communication methods in medicine in the beginning of the 1980s. This was due to the compatibility difficulties of different manufacturers' devices between each other. [32] The first standard was introduced in 1983 and it is still constantly updated and it has been renamed to Digital Imaging and Communications in Medicine (DICOM) standard.

The purpose of the standard was and is to unify the communication and management of medical imaging information and related data. When the images are in the same format they can be saved and downloaded with any device to a picture archiving and communication system (PACS) which follows the DICOM standard. With DICOM standard different device models of the same manufacturer or different manufacturers' devices can communicate with each. Although, DICOM standard gives the manufacturers some standards what the device should achieve, it does not mention how these standards are supposed to be attained.

In the DICOM standard (PS 3.14) the Grayscale Standard Display Function (GSDF) is defined [33] which helps in the consistent presentation of grayscale medical images in any DICOM-compatible display device. American Association of Physicists in Medicine (AAPM) uses this GSDF in their recommendations for monitor display quality control. GSDF will be discussed more thoroughly in chapter 5.

4.2 American Association of Physicists in Medicine

AAPM promotes the physics in medicine and biology, and one of its primary goals is the identification and implementation of improvements in patient safety for the medical use of radiation in imaging and radiation therapy. AAPM is a scientific and professional organisation which publishes two journals related to medical physics and produces technical reports on specific topics of medical physics. These technical reports are produced by nominated task groups and one of these technical reports handles the assessment of monitor display quality control in medicine. [1]

According to the AAPM report published in 1994, the responsibility of monitor displays quality and their quality control belongs to the medical physicists [16]. Although required from the medical physicists, there were no prior standards or recommendations which to follow in the display quality control. Therefore AAPM formed the Task Group 18 (TG18) to provide standard guidelines for the performance evaluation of the display devices in medical use.

4.2.1 Task Group 18

In 2005, TG18 published its report called "Assessment of Display Performance for Medical Imaging Systems". The report describes all the tests developed by the Task Group and how to perform them. The tests include both visually made evaluations and technical evaluations that require the use of special testing equipment, for example photometer. [4] The visual evaluations are of course subjective and they can be performed by anyone. These tests can however be used when the need of technical tests is considered.

The TG18 test patterns are widely in use and they were the basis of the measurements done in this research. The patterns used in the measurements are discussed in chapter 6. The original report and all test patterns (in .dcm and .tiff format) can be acquired from AAPM website (https://www.aapm.org/pubs/reports/detail.asp?docid=153).

4.2.2 Technical Standard for Electronic Practice of Medical Imaging

In 2007 American College of Radiology published "Technical Standard for Electronic Practice of Medical Imaging". The technical standard has been revised for several times and the newest version is from 2017 and it was revised by American College of Radiology, American Association of Physicists in Medicine and Society for Imaging Informatics in Medicine (SIIM). [27] The relevant part of the technical standard, for this thesis, is the revised recommendations of the luminance response. Theses recommendations are discussed in more detail in chapter 5, where the luminance response is considered.

4.2.3 Task Group 270 and 316

As the standard guidelines given by AAPM TG18 are over a decade old and the display technology in use has evolved drastically, CRT monitors have practically vanished, LCDs are currently majority and new technology (OLEDs) is entering the field, so an update is needed. The previous report handled many things that are characteristic to only CRT displays. For example, the resolution tests are quite pointless with LCD and OLED displays because the pixels are independent units and therefore not dependent from each other. In CRTs the principle of image formation is totally different, so the quality control of resolution is also important. To revise and update the standards, AAPM has formed a new Task Group No.270 called "Display QA" [2]. An example of new test pattern which will replace old LN and UN(L) test patterns (discussed in chapter 6) is shown in figure 4.1. The report can be expected within few years.

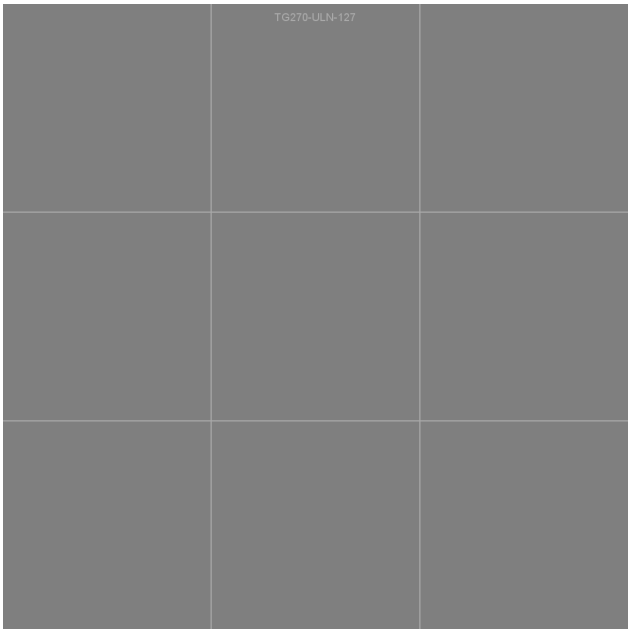

Figure 4.1. *New test pattern TG270-ULN-127. [5]*

As discussed before ultrasound imaging is part of radiology but surprisingly the same standards and requirements are not applied for it as are for x-ray imaging. Perhaps this has something to do with the fact that no ionising radiation is used in ultrasound imaging or it is thought that the the display does not have to fulfil the diagnostic display requirements as it is used for the acquisition of the image.

Whatever the reason AAPM has acknowledged this problem and they have formed Task Group 316 (TG316) named "Ultrasound Modality-Specific Display Presentation Consistency" to come up with standards for ultrasound displays. The new criteria for ultrasound modality will be based on the guidelines given in the new report of TG270. This report can also be expected to be published within few years. [3]

4.3 Finnish legislation and authorities

In Finland the legislation has given and obligated the Finnish Radiation and Nuclear Safety Authority (fi. *Säteilyturvakeskus*, STUK) to give orders, make recommendations and provide guidance in matters dealing with radiation and radiation safety. In the radiation law ultrasound is equated with non-ionizing radiation. However, STUK has given orders and guidelines for mainly ionizing radiation and its applications, and almost completely ignored medically used non-ionizing radiation applications.

The regulations and guidelines that STUK gives are called Regulatory Guides on radiation safety (fi. *Säteilyturvaohjeet*, ST-guides). In the ST Guide 3.3 the quality assurance of x-ray imaging is commented vaguely: "The functionality and technical condition of the X-ray equipment and its accessories (e.g. image receptor and display monitor) must be monitored by using quality assurance measures and continuously during the operation." [35]

To provide guidelines for the quality control of display monitors used in x-ray imaging, STUK published a guide "Healthcare x-ray equipment quality control guide" in 2008. In the guide, some of the AAPM tests are recommended but the whole procedure is considered to be too heavy as a normal quality control protocol. The tests recommended in the guide are shown in table 4.1. [36]

Although, STUK provided these guidelines for which tests to perform it did not take a stance about the reference values of the acquired results. Not until 2014, when they released "Mammography equipment quality control guide", STUK commented the reference values for any measurements. In this guide was given, what the minimum value of maximum luminance should be, and it was the same as AAPM's recommendation [37]. The reference values are discussed in chapter 5.

Currently the Finnish radiation law is being updated to fulfil the requirements of European Union's new radiation safety directive. The directive only deals with ionizing radiation so the new legislation in itself will not probably affect the quality control of ultrasound device monitors. However, simultaneously STUK will replace all their old ST Guides with new binding orders and guides.

In 2015 STUK did a survey about the reform needs for the new radiation law. In the report "Questionnaire for operators of radiation legislation reform needs". Although, the directive deals only with ionizing radiation, the old radiation law and regulations deal also with non-ionizing radiation, so there was also a part about non-ionizing radiation on the survey. The answers suggested that the medical use of non-ionizing radiation should be more regulated and on the free feedback it was stated that the quality control of magnetic resonance and ultrasound imaging devices should be statutory. These answers lead to the conclusion that the monitoring of magnetic resonance and ultrasound imaging should be discussed and experts on these fields should be heard about it. [19]

Due to the renewal of old the guides and the wishes from medical sector that ultrasound should also have same required quality control, Finnish authorities should acknowledge this need for guidelines and develop them. STUK mainly comments matters that are related to ionizing radiation but as the lead authority in Finland they should address this need somehow. As new radiation law has not passed yet, the development will most likely take a while but hopefully something will be done.

Table 4.1. *Tests recommended by STUK. Modified from [36]*

	Test or property	**Purpose**	**Recommended interval**
User tests	Operating environment	Check the viewing conditions of display	1 week
	Visual overall assessment	Check the displays performance visually from test image	1 week
	Other tests recommended by the manufacturer		
Technical tests	Operating environment	Check the viewing conditions of display	1 year
	Visual overall assessment	Check the displays performance visually from test image	1 year
	Luminance uniformity	Check the luminance uniformity (image brightness) from the whole display area	1 year
	Other tests recommended by the manufacturer		
Other possible tests	Luminance response		1 year (The displays from which radiologists perform diagnoses)
	Acceptable viewing angle Distortion of image Veiling glare Colours of display Pixel errors Bit depth Flickering		If necessary

5. PERFORMANCE PARAMETERS

As discussed in the previous chapter, AAPM has developed guidelines for what parameters should be considered when assessing the technical performance of display monitors. These guidelines are the most commonly followed and they also provide reference values for the measured parameters. [4] These guidelines also provide the baselinesfor which the Finnish Radiation and Nuclear Safety Authority also bases their own recommendations [36]. These measurable parameters and their reference values are discussed in this chapter.

As only photometric quantities will be discussed in this and the later chapters the subscript v will be dropped from the illuminance and luminance variables and they will be referred to only with E and L.

5.1 Luminance

A simplified definition of luminance is the quantity of light emitted by the display. A specific definition of luminance was provided in chapter 2.

Luminance response is the relationship between the input values of the system and the corresponding displayed luminance. The displayed luminance includes both the luminance produced by the display, which varies between minimum luminance L_{min} and maximum luminance L_{max}, and the luminance reflected from the display surface L_{amb}. As the amount of illuminance E affects the amount of reflected light L_{amb} they are discussed more thoroughly together in the next section. Now the luminances detected from the display are

$$L'_{min} = L_{min} + L_{amb}, \tag{5.1}$$

$$L'_{max} = L_{max} + L_{amb}, \tag{5.2}$$

$$L'(p) = L(p) + L_{amb}, \tag{5.3}$$

where $L(p)$ is the luminance response function. The the L' values are the luminances that are observed by the eye and they include the measured luminance L and the reflected luminance L_{amb}.

Luminance ratio is the ratio of maximum and minimum luminance

$$LR' = \frac{L'_{max}}{L'_{min}}. \tag{5.4}$$

When the ambient lighting is low or it is blocked by making the measurements with contact luminance detector the L_{amb} part is omitted from equations (5.1) - (5.3), and the luminance ratio, equation (5.4), becomes contrast ratio

$$CR = \frac{L_{max}}{L_{min}}. \tag{5.5}$$

As luminance ration depends on the ambient lighting manufacturers can not report it. Instead they can provide the contrast ratio of the display.

In the TG18 report AAPM gave recommendations for luminance and luminance ratio values. For primary displays $L'_{max} > 171$ cd/m^2 which is based on ACR recommendation and for luminance ratio $LR' \geq 250$. For secondary displays $L'_{max} \geq 100$ cd/m^2 and $LR' \geq 100$. Also, for both displays should be $L'_{min} \geq 1.5\ L'_{amb}$ and ideally $L'_{min} \geq 4\ L'_{amb}$. [4]

In the ACR-AAPM-SIIM technical standard the recommendations are more strict. For primary displays which are not used for interpretation of mammograms recommendations are $L'_{max} \geq 350$ cd/m^2, $L'_{min} \geq 1.0$ cd/m^2 and $L'_{min} \geq 4\ L'_{amb}$. For monitors in other use, in other words secondary displays, $L'_{max} \geq 250$ cd/m^2 and $L'_{min} \geq 0.8$ cd/m^2. If the maximum luminance of monitor is brighter, then the minimum luminance should also be larger so that the luminance ratio stays the same. [27]

As the luminance ratio affects how many different grayscales can be displayed, the ratios should fulfil the recommended values to ensure that enough grayscales are displayed. If same images are viewed from several different monitors the luminance ratios should be as close to each other as possible to ensure the consistency of the viewed images. Although, the larger luminance ratio means more grayscale values an excessively large ratio exceeds the range of visual system and therefore does not have any clinical impact [27].

Because many different grayscale values are shown it is important that the displayed luminance is uniform. Otherwise a contrast between different regions could be perceived, although an uniform image is displayed. Luminance uniformity describes the difference of measured minimum and maximum luminance compared to their average values and AAPM defines it as

$$\text{Luminance uniformity}(\%) = 100\ \% \cdot \frac{L'_{max} - L'_{min}}{\frac{L'_{max} + L'_{min}}{2}}. \tag{5.6}$$

In LCDs, the non-uniformity of luminance comes mostly from the non-uniformity of the backlight and differences in single pixels.

As human visual system is not very sensitive to very low spatial frequencies, it is not a problem if the variation occurs gradually over the whole display area. Due to this AAPM

suggests that the luminance uniformity can be as high as 30 %. This does not account if the changes are significant in smaller range so that the non-uniformities are clearly visible. In this case corrective actions should be taken. Although, as high as 30 % uniformity is acceptable it should be noted that if the variations are large then the display most likely will not be GSDF compliant. [4]

5.2 Illuminance and ambient luminance

Illuminance is the radiant flux per unit area and it was discussed more precisely in chapter 2. The incoming light has an enormous effect on the perceived image quality. The incoming light is reflected from the screen and thus weakens the observed contrast [9]. The reflections include both overall lighting and single objects like white coats of the staff or singular bright light sources.

The incoming light is reflected in two different ways from the screen material. In specular reflection all light is reflected and the reflection angle is same as the incident angle. In specular reflection a clear image of the reflected object is formed on the display surface which disturbs the perceived contrast locally. A good example of specular reflection is the white coat of doctors. The other way of reflection is diffuse reflection. In diffuse reflection, the light is reflected in every direction so that overall brightness is observed and no clear objects are formed. The diffuse reflection can occur due to rough surface but it is possible that diffuse reflection is still present although the surface is smooth. Even with smooth surfaces some objects do not reflect the light in a specular way. This is because the light penetrates the surface of the material and it is refracted and reflected several times in the material which causes it to reflect light approximately uniformly in all directions.

Due to the reflections lighting conditions and luminance level affect directly to the observed luminance. This reflected component of perceived luminance is called ambient luminance L_{amb}. The ambient luminance depends linearly from illuminance E and reflection coefficients R_d for diffusive reflection and R_s for specular reflection. These coefficients can vary greatly between different displays. In the AAPM TG18 report it is proposed that the level of ambient luminance can be approximated with the equation (5.7). [4]

$$L_{amb} = ER_d \tag{5.7}$$

In 2013 Matsuyama et al. [24] studied the effect of ambient lighting on LCDs. The displays used in studies had different kinds of surface treatments: glare, anti-glare and anti-reflection. As results they got the coefficients of diffuse and specular reflections for each display type. The diffuse reflection coefficients varied between 0,0010 and 0,0018 cd/(m$^2\cdot$ lux), and the specular reflection coefficients varied approximately between 0,005 and 0,05 cd/(m$^2\cdot$ lux).

There are no same kind of limits for the illuminance level as for other parameters because the effect depends on the reflection properties of the display as described in chapter 5. In the AAPM TG18 report the maximum illuminance values depend on the luminance range L_{min}-L_{max} and the reflection coefficients of the display. The closest luminance range corresponding to measurements is 1-250 cd/m^2. The maximum room lighting, based on specular reflection varies between 2 and 42 lux and based on diffuse reflection varies between 4 and 50 lux. [4]

In the revised technical report, the illuminance level is discussed in "Ergonomic factors" part and it is recommended that the illuminance is set to 25 to 50 lux. This range is based on research done by Brennan et al. in 2007 [7] and Polard et al. in 2012 [29].

In 2004 Goo et al. studied the effect of monitor luminance and ambient lighting in soft-copy readings of digital chest radiographs. They tested the detection of three different abnormalities with different monitor luminances and ambient lighting levels. The illuminance values were 0 lux, 50 lux and 460 lux. In only one of the three abnormalities they there was statistically significant difference due to ambient light. [14]

When luminance level was 25 lux and 40 lux, lower numbers of false-positive and false negative findings were done when compared to illuminance levels of 100 lux and 480 lux. Similar results to higher illuminance levels were also acquired when the illuminance level was 7 lux. Hence, the illuminance level should not be too low. The effects of very low or high illuminance can be compensated with the experience of radiologists. [7]

Pollard et al. studied in 2012 if slightly elevating the ambient lighting would have some kind of effect on diagnostics. They used illuminance levels of 1 lux and 50 lux and used DICOM calibrated monitors. The results were that there was no statistically significant difference in detection and detection speed of nodules in chest radiographs when ambient lighting was changed. [29]

As a conclusion, at least on moderate illuminance levels the ambient lighting does not have a significant effect on performance when examining digital radiographs. Although, really low or really high ambient lighting could affect the fatigue of the eyes and therefore is at least an ergonomic factor which should be considered.

5.3 Grayscale Standard Display Function

An image can be coded and transmitted as digital signal and reconstructed accurately but the displaying of the image is dependent of the displaying hardware. In DICOM-standard PS3.14 a relationship between pixel value and displayed luminance was developed. The function that maps pixel values to luminances is called grayscale standard display function. The function is based on various measurements and models of how an average human perceives luminances from a wide range. As the functions takes into consideration the contrast sensitivity of human eye, it does not map the pixel values linearly to luminances.

Eyes is more sensitive to the differences in luminance on higher luminance levels. This means that the change in luminance on lover levels needs to be larger to produce a perceivable difference than on higher levels of luminance. The GSDF takes this into consideration and a change in presentation value corresponds to equal changes in the observed brightness. [31]

When the possible mathematical functions for the Grayscale Standard Display Function were considered, the conditions were that the it should be presented by only one function which can cover the entire luminance range of interest. The function should also be continuous and monotonic. Another objective was that the function should provide similarity in the displaying of the grayscales in devices with different luminance ranges.

The GSDF is derived form Barten's model which luminance range is 0,05 - 4000 cd/m^2 and this is divided to 1023 just-noticeable difference (JND) indices [31]. The term just-noticeable difference is used in experimental psychophysics to describe the minimum amount by which stimulus intensity must be changed in order to produce a noticeable variation in sensory experience. The GSDF gives the relation between JND-indices and displayed luminance values and it is presented in figure 5.1 and defined as:

$$\log_{10}L(j) = \frac{a + c\cdot\ln(j) + e\cdot(\ln(j))^2 + g\cdot(\ln(j))^3 + m\cdot(\ln(j))^4}{1 + b\cdot\ln(j) + d\cdot(\ln(j))^2 + f\cdot(\ln(j))^3 + h\cdot(\ln(j))^4 + k\cdot(\ln(j))^5}, \quad (5.8)$$

where j is the JND-index (from 1 to 1023), $L(j)$ the corresponding luminance, ln is natural logarithm and the constants are:

$$\begin{aligned}
a &= -1,3011877,\\
b &= -2,5840191\cdot10^{-2},\\
c &= 8,0242636\cdot10^{-2},\\
d &= -1,0320229\cdot10^{-1},\\
e &= 1,3646699\cdot10^{-1},\\
f &= 2,8745620\cdot10^{-2},\\
g &= -2,5468404\cdot10^{-2} \text{ and}\\
h &= -3,1978977\cdot10^{-3}.
\end{aligned}$$

As luminance values are measured when comparing the displays to the standard, it is more convenient to present the equation the other way around, in other words, the JND index as function of luminance:

$$\begin{aligned}
j(L) =& A + B\cdot\log_{10}(L) + C\cdot(\log_{10}(L))^2 + D\cdot(\log_{10}(L))^3 + E\cdot(\log_{10}(L))^4 +\\
& F\cdot(\log_{10}(L))^5 + G\cdot(\log_{10}(L))^6 + H\cdot(\log_{10}(L))^7 + I\cdot(\log_{10}(L))^8, \quad (5.9)
\end{aligned}$$

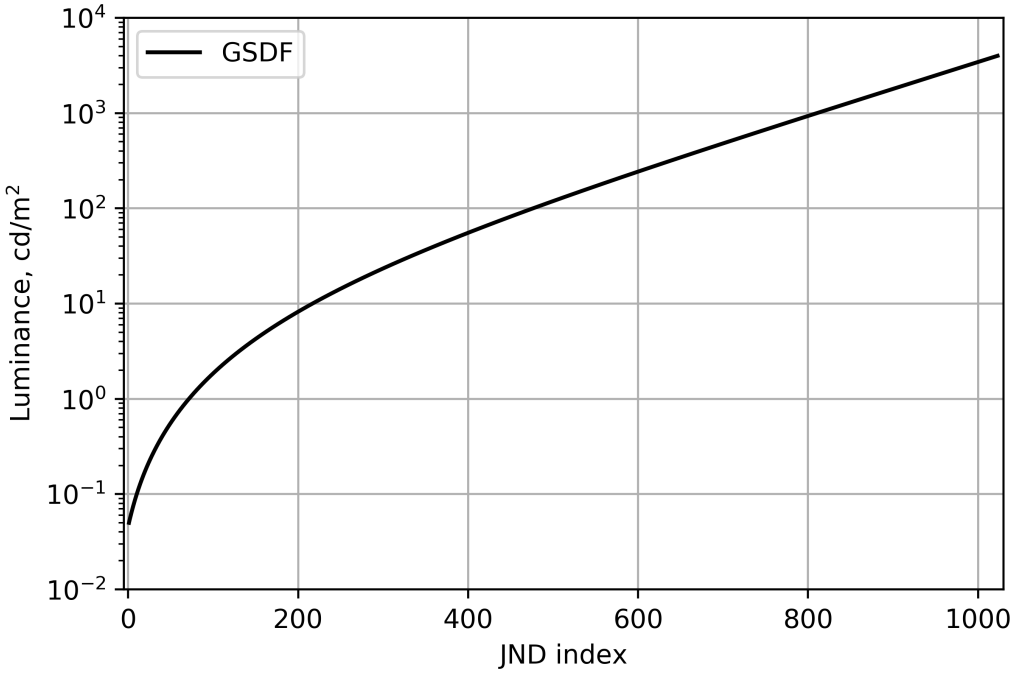

Figure 5.1. *Grayscale Standard Display Function: Luminance as function of JND index.*

where L is the measured luminance value and the constants are:

$$\begin{aligned} A &= 71,498068, \\ B &= 94,593053, \\ C &= 41,912053, \\ D &= 9,8247004, \\ E &= 0,28175407, \\ F &= -1,1878455, \\ G &= -0,18014349, \\ H &= 0,14710899 \text{ and} \\ I &= -0,017046845. \end{aligned}$$

To compare the test patterns and their p-values to the measured luminances and the corresponding JND indices, the other one of these, p-values or JND indices, needs to be converted to the other one. In this thesis it was chosen that the JND indices are converted to p-values. The conversion is linear and the relationship of these variables is presented in equation (5.10).

$$J_i = J_{min} + \frac{P_i(J_{max} - J_{min})}{\Delta P}, \tag{5.10}$$

where J indicates the JND indices, P is the p-value and ΔP is the change in p-value. The JND indices can be calculated from the measured luminances with equation (5.9).

According to AAPM recommendations all the measured points for primary displays should be within the 10 % margin of difference and secondary displays within the 20 % margin of difference (figure 5.2).

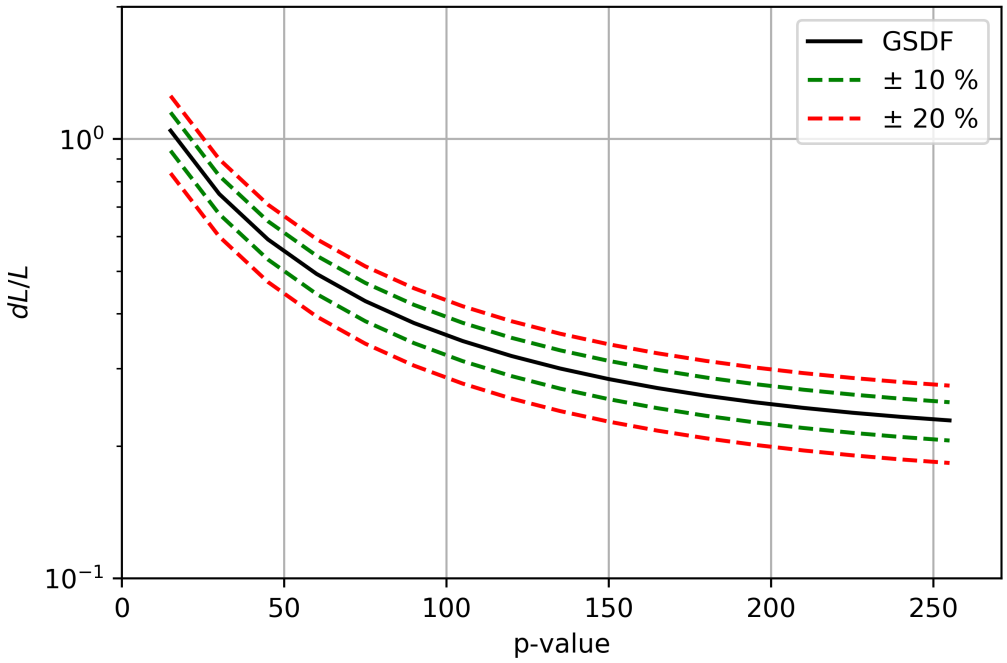

Figure 5.2. *Grayscale Standard Display Function: Change of luminance per p-value as function of p-value.*

6. METHODS

The measurement device and its operating principle are presented in this chapter. Also the test patterns and the measurements they are used for are presented and finally the devices and the display settings are discussed.

6.1 Measurement device

The luminance and illuminance measurements were performed with Unfors Xi (Sweden) measurement device. Two different devices were used, one in Seinäjoki and another one in Tampere and few measurements in Seinäjoki as their own device was sent to be calibrated. Different kinds of detectors can be connected to the same base unit with USB cable. The same light detector was used to measure both luminance and illuminance.

To measure contact luminance the optical tube needs to be attached to the light detector, so that the solid angle is limited and well defined. To measure illuminance, the optical tube needs to be detached. The measurement device, with detached optical tube, is presented in figure 6.1. As the luminance is measured with contact luminance detector the ambient lighting is blocked so that $L_{amb} = 0$. To compensate this, the quantity of ambient luminance reflected from the screen L_{amb} was measured from turned off display at approximately 15 cm distance and lighting set to normal scanning conditions. Although, the method might not be very accurate, it was chosen to get some insight about the level of L_{amb}. As measured in this way, the value includes both specular and diffuse reflection of light.

The Tampere University Hospital's device was calibrated in 16.09.2014. The accuracy of both luminance and illuminance measurements is given in the calibration certificate and it is ± 3 %.

The Seinäjoki Central Hospital's device was calibrated in 21.05.2018 The accuracy of both luminance and illuminance measurements is given in the calibration certificate and for luminance it is 1,8 % and for illuminance it is 2,0 %. The reference instruments are traceable to SP Technical Institute of Sweden providing traceability to international standards.

The measurement range of luminance is same for both devices, 0,05 - 50 000 cd/m^2 and the resolution is 0,01 cd/m^2. Both devices also comply with the CIE standard photopic spectral response within 4 %. This is one percentage point higher than the AAPM requirements [4]. Otherwise the devices fulfil the AAPM requirements.

Figure 6.1. *Unfors Xi measurement device and its components. From left to right: Base unit, light detector and optical tube.*

6.2 Test patterns

In their report, the Task Group 18 presented 20 sets of test patterns with total of 59 images and additionally three sets of anatomical images with total of five images. As discussed before, not all of the tests are relevant for LCDs and if all relevant would be chosen the amount of tests would still be quite large. Therefore, three (or four) sets with the total of 21 (or 23) images was chosen for this work. The used sets of patterns are discussed below and finally some of the other relevant patterns are discussed briefly. All the patterns are named TG18-XXYY-ZZ, where XX is name of the pattern set, YY is the bit depth of the displayed values and ZZ is the number of the image in the set. Options for bit depth are 8 bits and 12 bits.

The test patterns are designed to fill the whole screen or at least the part of the screen where the image is displayed. AAPM provides test patterns in two sizes 1024x1024 pixels and 2048 pixels. For most patterns it is essential that the relationship between image pixels and display pixels are one-on-one. This holds especially for resolution patterns. When the luminance response is assessed, the resolution is not so important and the patterns can be magnified to fit the whole display area. [4]

All the patterns are shown in a lot smaller scale than in the measurements and not in a proper format on a properly calibrated display, so details of the patterns, especially TG18-QC, may be unclear or may not be detected. But as picture tells more than a thousand words, they are still presented to give a little insight about the measurements.

6.2.1 TG18-LN patterns

The TG18-LN set contains 18 images which are used to assess the luminance response of a display. Three of the 18 test patterns are displayed in figure 6.2. Each of the patterns have the test region in the middle which covers 10 % of the whole image area. Depending on the bit depth, the centre's pixel values are 0, 15, 30, ... and 255 or 0, 240, 480, ... and 4080, and surrounding area's pixel value is either 153 or 2448. This corresponds to the 20 % of maximum luminance if the display is properly calibrated and follows the GSDF.

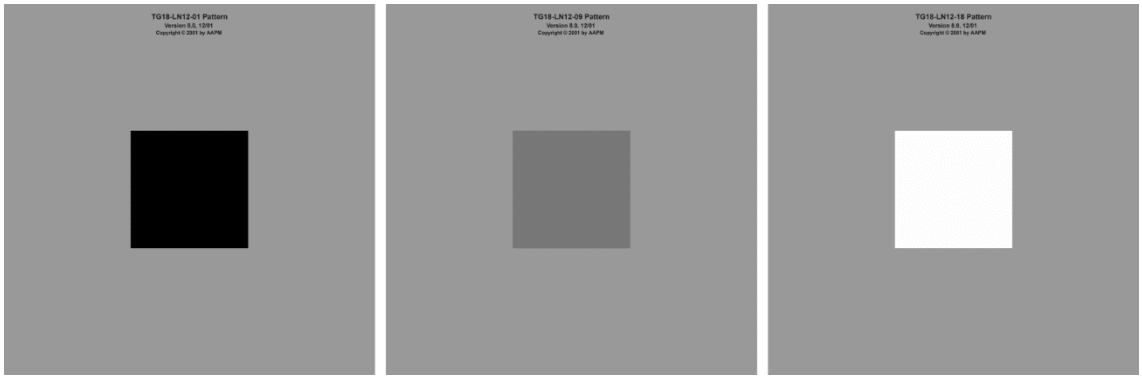

Figure 6.2. *Schematic of the three LN patterns. From left to right: TG18-LN12-01, TG18-LN12-09 and TG18-LN12-18.*

In the measurements the pattern filled the whole area where the ultrasound images were displayed although this was not always in the middle of the screen. AAPM recommends to measure all the 18 images so that there would be enough data points to evaluate if the display follows GSDF. The darkest and brightest patterns were also used to determine minimum and maximum luminances and further from these the contrast and luminance ratios are obtained.

6.2.2 TG18-UN(L) patterns

Two sets, UN and UNL are almost identical with a minor difference. The both sets contain two test patterns which are uniform and their pixel values correspond 10 % and 80 % of the maximum luminance value. The only difference is that the UNL patterns have low contrast lines to identify the central and four corner areas which each covers 10 % of the total area. These patterns were used to measure and define the luminance uniformity of the display area. To define the luminance uniformity, the luminance is measured from all the corners and from the middle.The patterns were also used to check for dead pixels as white pixels can be easily detected from UN(L)10 pattern and black pixels from UN(L)80 pattern. Three of the four test patterns are presented in the figure 6.3.

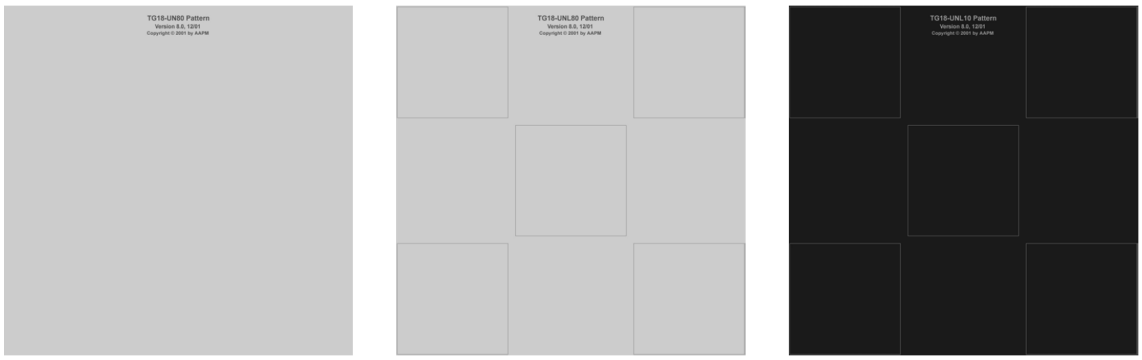

Figure 6.3. *Schematic of one UN and two UNL patterns. From left to right: TG18-UN80, TG18-UNL80, and TG18-UNL10.*

6.2.3 TG18-QC pattern

The TG18-QC pattern (see figure 6.4) was developed for routine visual evaluation of the displays. It is used for quick overall display quality assessment so that the evaluations could be performed more frequently for example every week. The pattern has several parts for different kinds of tests. The grid lines everywhere in the image are meant for inspection of geometrical distortions. This test is mainly for the CRT displays as LCDs do not have any geometrical distortions if the image resolution is the same as native resolution of the display.

The 16 uniform patches with varying pixel values are meant for evaluation of luminance response. Each patch has small patches in every corner. Upper left and lower right have pixel values a bit higher than the large patch and upper right and lower left have pixel values a bit lower than the large patch. There are also two patches with minimum and maximum pixel values and embedded in them internal patches with pixel values corresponding to 5 % and 95 %.

Line-pair patterns and "Cx" patterns in the middle and every corner are meant for resolution evaluation. The "Cx" patterns have scoring references in the middle for which they should be compared to.

The "QUALITY CONTROL" texts on minimum, mid-point and maximum pixel value backgrounds are for contrast and detail evaluations. Different letters have different contrasts. Following how many letters can be seen is easy way to notice the waning of maximum luminance. As the waning is slow, eyes get used to it and it is difficult to notice before it is "too late".

To evaluate bit depth and contouring artefacts there are two vertical bars with continuous pixel values variation. If any clear edges can be seen in the bars there appears to be some sort of error for example miscalibrated gray level or bit depth configuration error.

The white and black bars are for evaluating video signal artefacts and the horizontal area at the top centre of the pattern is for visual characterisation of cross talk in flat-panel displays.

In the measurements an overall check was made from the image but the focus was on the luminance response patches and contrast-detail "QUALITY CONTROL" texts.

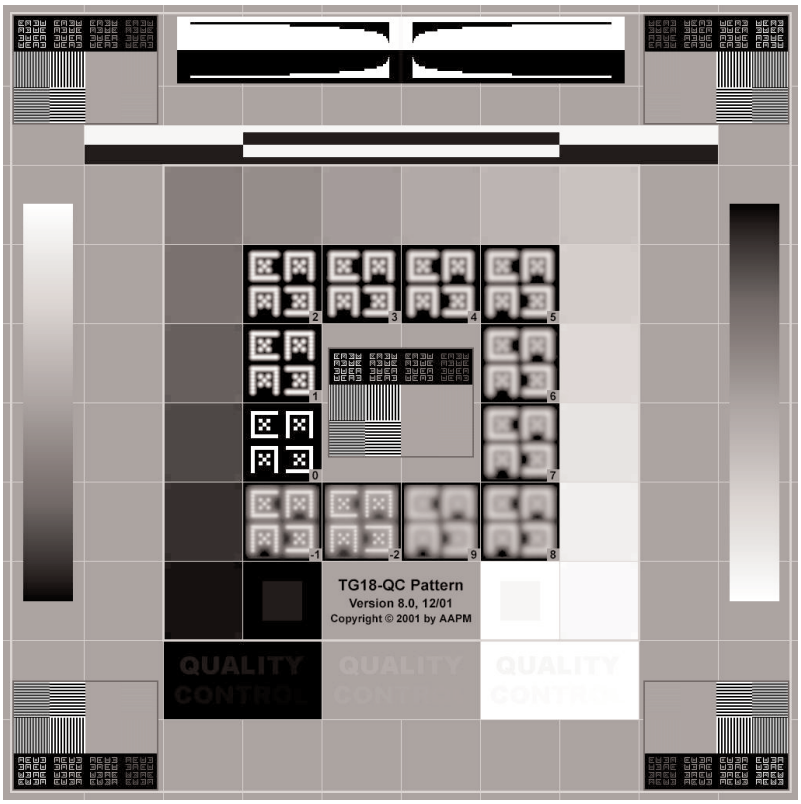

Figure 6.4. *Schematic of the TG18-QC test pattern.*

6.2.4 TG18-CT

The TG18-CT test pattern (figure 6.5) was not used in the measurements but it is relevant for the luminance response and viewing angle evaluation so it is discussed here shortly.

The test pattern has 16 patches varying in luminance. Every patch has low contrast smaller patches in every corner identical to those in TG18-QC pattern. In addition, each patch has a very low contrast half-moon target in the middle. As discussed in chapter 3 some LCDs, depending on the technology, have fairly limited viewing angles. This test pattern can be used to evaluate the suitable viewing angles by looking at the pattern and changing the viewing angle. When any of the half-moon targets ceases to appear, that is the limit of the viewing angle and the monitor should not be viewed from larger angles. This test can be done both horizontally an vertically.

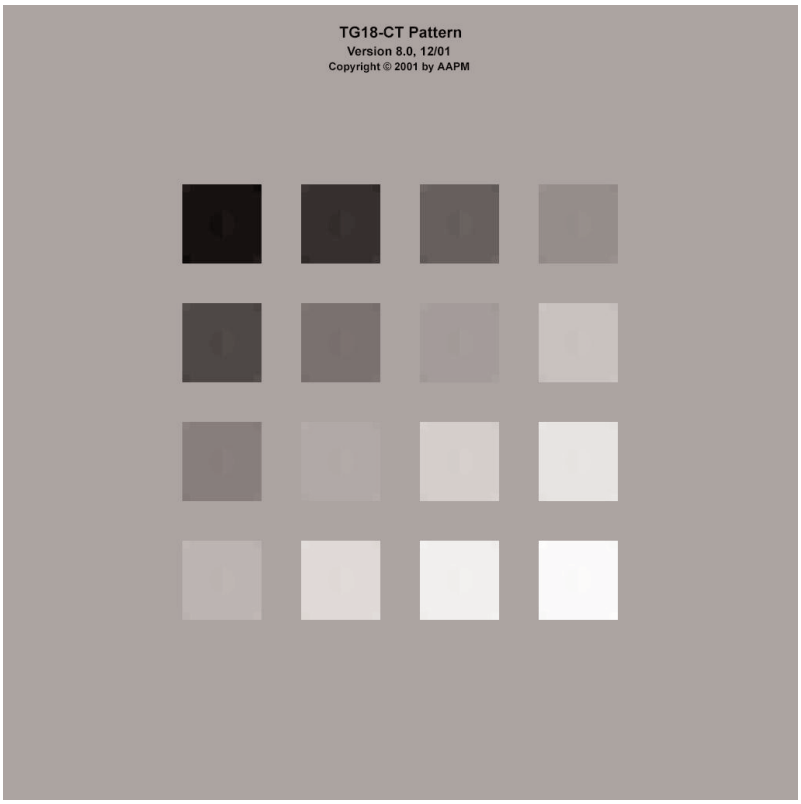

Figure 6.5. *Schematic of the TG18-TC test pattern.*

6.3 Illuminance

Illuminance, in other words the light from the surroundings, was measured with the same Unfors Xi device. The optical tube was detached from the detector and the detector was placed on the surface and in the middle of the screen. As the measurement is very sensitive to the objects in front of the light sources and reflections from any surfaces, the measurements were quite difficult to perform very accurately and the value varied sometimes.

If doctors or nurses were available, they were asked to adjust the lighting to appropriate level used in examinations. Some staff members pointed out that the lighting can vary quite a lot between different exam performers, exams and depends also on the daylight. As extreme lighting is very seldom used, the measurements were performed with the most common or average lighting.

If no staff members who perform exams were available, the illuminance was measured in lighting defined by the measurer. As there was some prior experience based on the previous measurements, the lighting was set to mimic the previous experiences. The reflected ambient lighting was also measured in the same conditions.

6.4 Measured displays

All the devices had colour display monitors and it was unknown, if any of the monitors were DICOM calibrated. Any information about the displays was searched from the devices' manuals but practically nothing useful was found (and for some devices there seemed to be even minor errors. For example for Philips Affiniti 70 there are 6 brightness options in manual but in reality there are 7 and the last one is darker than the previous.)

All the devices were manufactured either by GE Healthcare or Philips. This was due to the fact that other brands (Acuson, Esaote and Samsung) did not support the importing of the test patterns from CD or USB flash drive or did not have test patterns in their internal memory. These problems were also encountered in some of the GE's and Philips' device models. All the measured devices are listed in table 6.1. As it does not matter where each device is located they are not specified by location or serial number in the table.

As there was no prior information if the displays were DICOM calibrated or at which settings, the measurements settings were standardised at beginning of the measurement process. Maximum brightness was used as otherwise many of the displays would not have passed the minimum criteria for maximum luminance. Although, none of the older displays passed the criteria of primary displays and some did not even pass the secondary display criteria. For newer Philips' monitors (Affiniti and EPIQs) it was possible to change the black level, which was set to minimum value. The increasing the black level increases the brightness of darker greyscales. There were no clear instructions about which range the black level affects but it was noted that it had no effect on maximum luminance.

In GE's monitors the gamma could be adjusted. The gamma value is related to the function that maps pixel values to certain luminance values. This lead to the realisation that GE's monitors could not even be DICOM calibrated as the GSDF is different from the possible gamma curves as demonstrated in figure 6.6. The default value $\gamma = 2.4$ was used in the measurements.

Table 6.1. *List of measured devices.*

Device	Manufacturer	Model	Year of purchase
1	GE	LOGIQ E9	2014
2	GE	LOGIQ E9	2011
3	GE	LOGIQ E9	2013
4	GE	LOGIQ E9	2013
5	GE	LOGIQ E9	2010
6	GE	LOGIQ E9	2010
7	GE	LOGIQ E9	2009
8	GE	LOGIQ E9	2009
9	GE	LOGIQ P9	2017
10	GE	LOGIQ S7	2012
11	GE	LOGIQ S8	2015
12	GE	LOGIQ S8	2018
13	GE	LOGIQ S8	2018
14	GE	LOGIQ S8	2013
15	GE	LOGIQ S8	2012
16	GE	LOGIQ S8	2012
17	GE	LOGIQ S8	2017
18	GE	LOGIQ S8	2017
19	GE	LOGIQ S8	2015
20	GE	LOGIQ S8	2015
21	GE	LOGIQ S8	2013
22	Philips	Affiniti 70G	2015
23	Philips	EPIQ 5C	2016
24	Philips	EPIQ 5C	2017
25	Philips	EPIQ 7C	2017
26	Philips	EPIQ 7C	2013
27	Philips	EPIQ 7C	2018
28	Philips	EPIQ 7C	2018
29	Philips	EPIQ 5G	2015
30	Philips	EPIQ 7G	2013
31	Philips	EPIQ 7G	2016
32	Philips	EPIQ 7G	2015
33	Philips	iE33	2012
34	Philips	iE33	2010
35	Philips	iU22	2012
36	Philips	iU22	2012
37	Philips	HD15	2010
38	Philips	HD15	2010
39	Philips	HD15	2010

The measurements were performed at several operational units of Pirkanmaa Hospital District (Tays Central Hospital, Tays Heart hospital, Tays Hatanpää hospital, Tays Sastamala Hospital, Tays Valkeakoski Hospital and Orivesi Health Centre) and The Hospital District of South Ostrobothnia (Seinäjoki Central Hospital and Alajärvi, Kauhava and Lapua Health Centres).

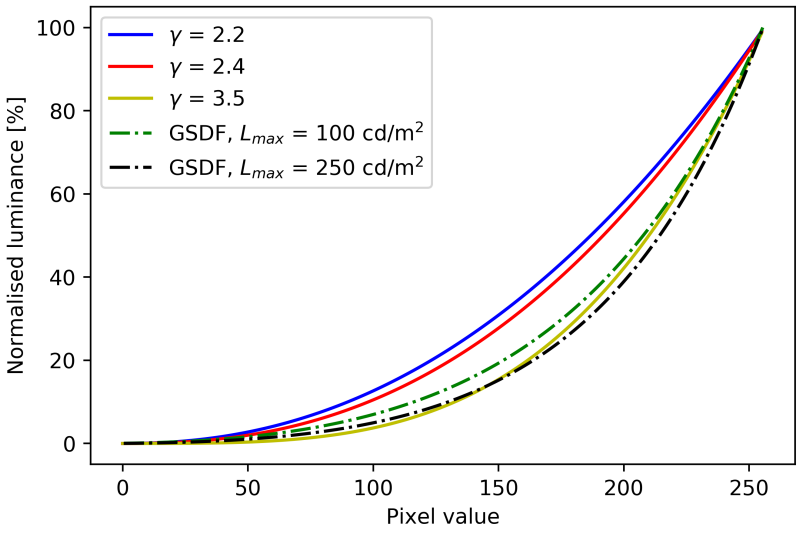

Figure 6.6. *Functions of mapping pixel values to normalised luminance with different gamma values and GSDF functions with different L_{max}.*

7. RESULTS

In this chapter all the results are discussed. All the results are collectively presented in tables A.1 and A.2. The chapter is divided similarly to chapter 5. First different luminance parameter values, luminance ratio as well as contrast ratio and the luminance uniformity are discussed. Then, the illuminance and its effects are considered. After that, the GSDF compliance and the deviation from it are discussed. Lastly, the visual evaluations are discussed. All the presented luminance values include the ambient lighting, L'_{amb} and it has been taken into consideration in the calculations except when contrast ratio is calculated. Results are presented mostly as bar graphs, so that they are easy to compare and to show the overall state of the displays.

When examining the GSDF compliance the displays from different manufacturer's devices are considered separately as Philips promises that their devices are GSDF compliant and GE does not. This difference is significant and it can clearly be observed from the measurement results.

All the measurement results are compared to the AAPM TG18 criteria [4] and the revised criteria [27]. The displays are classified as "Primary", "Secondary" or "Fail" if they pass or fail the certain criteria. When evaluating the ambient luminance and luminance uniformity a simple "Pass"/"Fail" evaluation is used. All these results are gathered together and presented in tables A.3 and A.4.

7.1 Maximum luminance

The maximum luminances, L'_{max}, are presented in figure 7.1. The values are colour coded based on the old AAPM TG18 criteria but the new criteria (top two black horizontal dashed lines) are presented also. Red means that the maximum luminance is lower than 100 cd/m^2, which was the minimum for secondary displays. Yellow means that 100 cd/m^2 $\leq L'_{max}$ $<$ 171 cd/m^2, in other words, that the display fulfils the secondary display criteria and green means that $L'_{max} \geq$ 171 cd/m^2 so it fulfils the primary display criteria. [4] The cyan bar means that 250 cd/m^2 $\leq L'_{max} <$ 350 cd/m^2, which is the revised secondary display criteria for minimum value of maximum luminance. For revised criteria 350 cd/m^2 is the minimum value for primary display luminance. [27]

All the maximum luminance L'_{amb} values are displayed in figure 7.1. The two upper black dashed lines show mark the new secondary and primary criteria and the two lower grey dotted lines mark the old secondary and primary criteria. As can be seen from the figure, only one display, which is only few months old, fulfils just barely the new maximum luminance criteria for secondary displays. In total there are 6 displays that do not fulfil the

old secondary display criteria, 16 devices that are good enough for secondary displays and 17 (including the one which fulfils the new secondary display criteria) that fulfils the old primary display requirements.

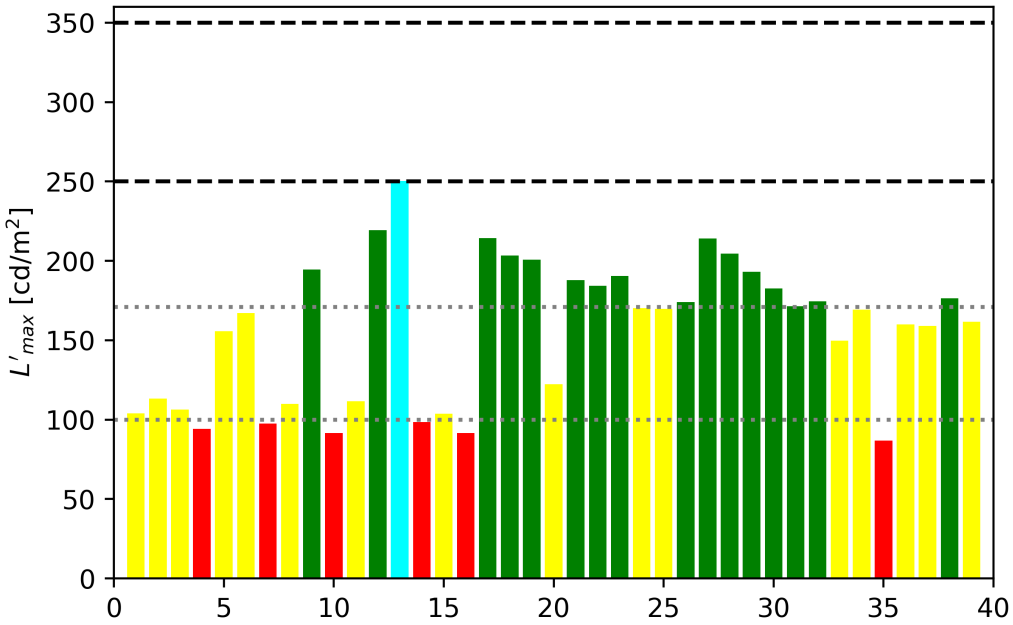

Figure 7.1. *Maximum luminances of the displays.*

7.2 Minimum luminance

In the AAPM TG18 report there are no explicit recommended values for minimum luminance but they are compared to ambient luminance. These criteria are used when evaluating the level of L_{amb}. In the revised technical report there are recommended values for minimum luminance L'_{min}. The criteria are for primary displays $L'_{min} \geq 1,0$ cd/m^2 and for secondary displays $L'_{min} \geq 0,8$ cd/m^2. The measurement results and the criteria are displayed in the figure 7.2. The bars are again colour coded: green if primary display requirement is fulfilled, yellow if secondary display requirement is fulfilled and red if the secondary requirement is not fulfilled. The secondary and primary criteria values are marked with grey dotted lines. In total 11 displays fulfil the primary display requirement, one fulfils the secondary display requirement and the rest 27 fail these requirements. It is notable that for most displays that pass the primary criteria it is due to the component of ambient lighting. For majority of the monitors the L_{min} is approximately same. For newer Philips' monitors the L_{min} value could be increased by increasing the black level, which would probably lead to most of the monitors to fulfil the criteria, unlike now.

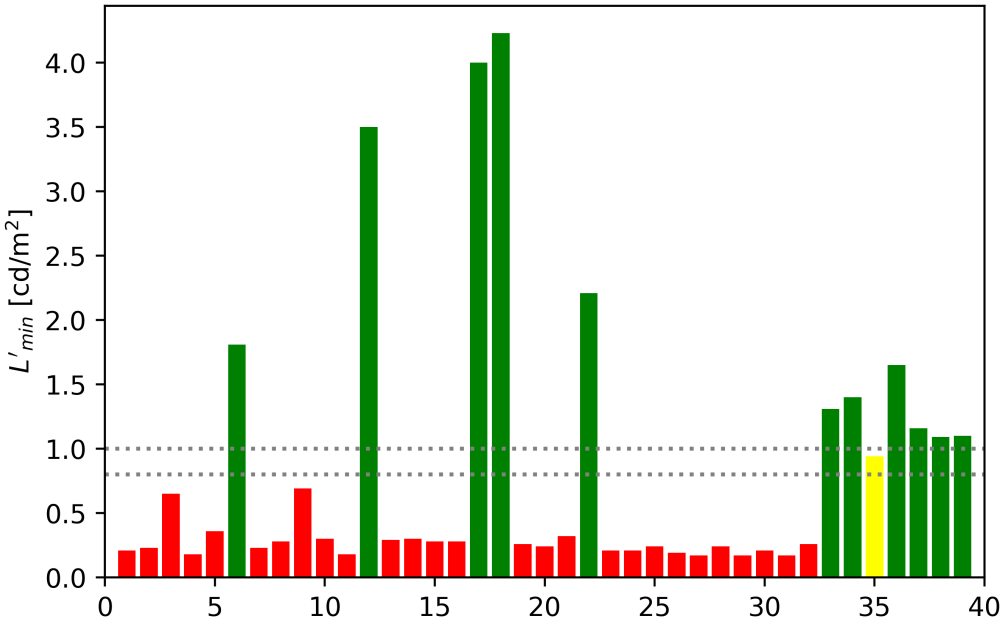

Figure 7.2. *Minimum luminances.*

7.3 Ambient luminance

As stated before L_{amb} is compared to L_{min} or L'_{min}. In TG18 report the given relations are $L_{amb} \leq 1,5\, L_{min}$ and $L_{amb} \leq 2,5\, L'_{min}$, and in the revised technical report $L_{amb} < 0,25\, L_{min}$. In the figure 7.3 measurement results are displayed. Both presented old requirements were used in the evaluation and if they were not fulfilled the bar is colour coded in red and if both were passed the bar is green. In total, 11 fail the both requirements and 28 pass them. When considering the new criteria the tables are turned. Only 16 pass and 23 fail the requirement. This is presented in figure 7.4.

All the measured L_{amb} values were not within the measurement range of the luminance meters (0,05 - 50 000 cd/m^2). There were 16 values that were below 0,05 cd/m^2 so they can not be assumed completely accurate. This error is quite insignificant as the effect to luminance ratio and everything else is very small between the range 0-0,04 cd/m^2.

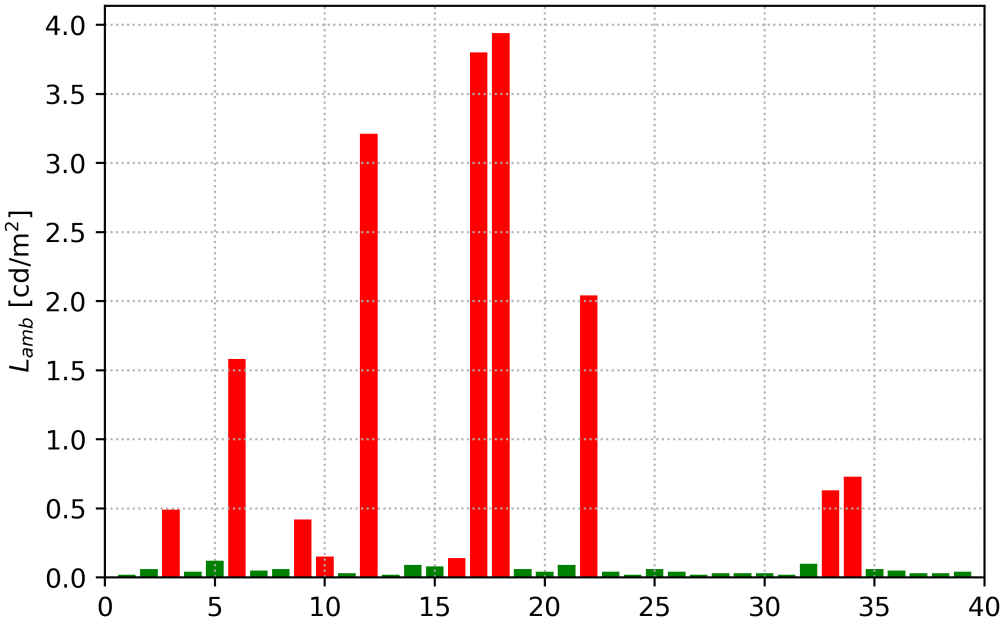

Figure 7.3. *Measured L_{amb} values colour coded based on old criteria.*

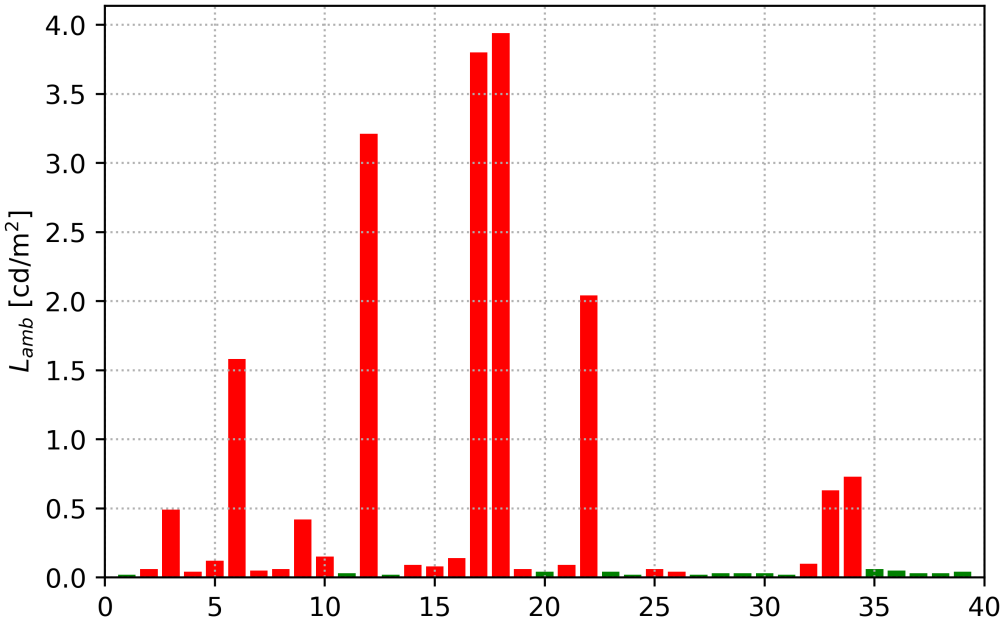

Figure 7.4. *Measured L_{amb} values colour coded based on new criteria.*

7.4 Luminance ratio and contrast ratio

The luminance and contrast ratios, calculated with equations (5.4) and (5.5), are presented in table A.1. The variation in both luminance and contrast ratios are great. Luminance ratios vary between 48 and 1260, and contrast ratios vary between 99 and 1427. The effect of ambient luminance can be seen easily as a large difference between luminance and contrast ratio.

In the AAPM TG18 report the recommendation for primary displays is $LR' \geq 250$ and for secondary displays $LR' \geq 100$ [4]. In the revised technical standard the corresponding values are 350 and 250 [27]. In the report it is also mentioned that an excessively large luminance ratio exceeds the capabilities of human eye and is therefore unnecessary. There are no guidelines, what excessive is, but here it will be considered as double of the revised primary display requirement. In other words if the value is larger than 700.

Contrast ratio of display is a good baseline to start when considering luminance ratio. If the contrast ratio is lower than the requirements or really close it is quite clear that the luminance ratio will not fulfil the requirements as L_{amb} is also taken into consideration. The contrast ratio of most displays, in total 32, was over 350, for one display it was between 250 and 350, for 5 displays it was between 100 and 250 and for one display it was below 100. The high contrast ratio values are due to the low values of L_{min}, not because of extremely high values of L_{max}.

When comparing to old AAPM TG180 criteria, in total 7 displays fail and 5 fulfil the secondary display criteria and the rest 26 fulfil the primary display criteria. And for the revised criteria 13 fail and 4 fulfil the secondary display criteria and the rest 22 fulfil the primary display criteria. Now, considering that the lower limit of excessive luminance ratio value is 700, in total 11 displays are over this. All the contrast and luminance rations are presented in figure 7.5.

Although, contrast ratio is a good starting point in needs to be remembered that if the minimum luminance L_{min} is very low, the ambient luminance L_{amb} has a remarkable effect on the luminance ratio. An extreme example is device 22, which contrast ratio is 1072 but luminance ratio is only 83. On the other extreme is device 36, which ambient luminance is only ~ 3 % of its minimum luminance, so there is no significant difference in contrast ratio (100) and luminance ratio (97).

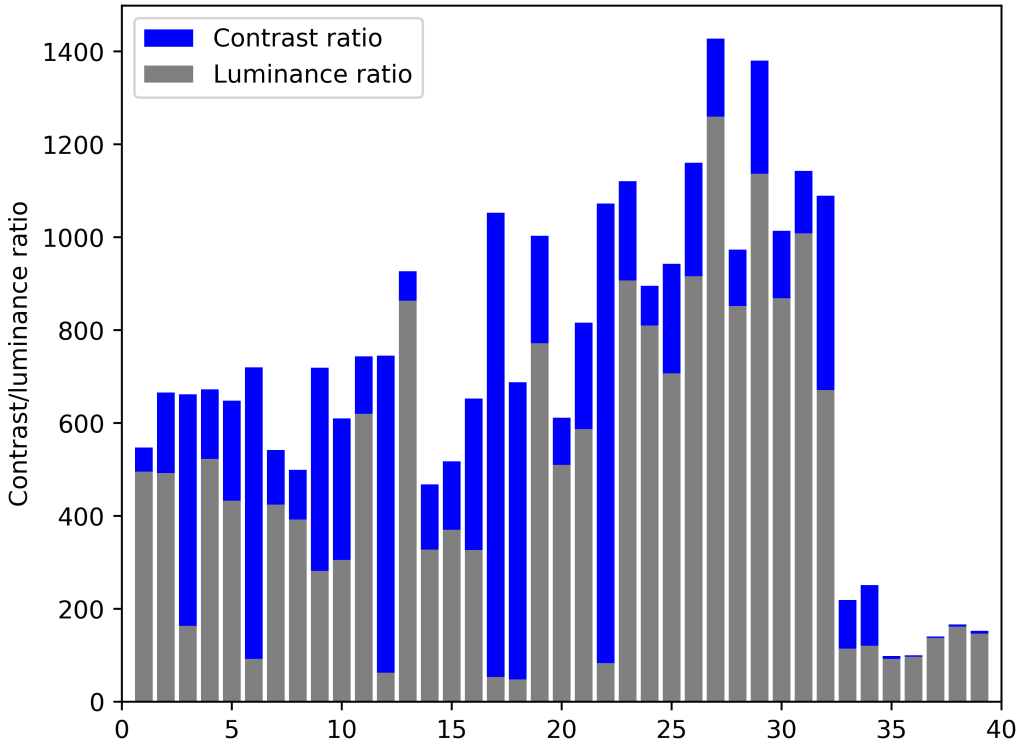

Figure 7.5. *Contrast and luminance ratios of devices.*

7.5 Luminance uniformity

The results for luminance uniformities, calculated with equation (5.6), are presented in figures 7.6 and 7.7. The figure 7.6 corresponds the measurements from TG18-UNL10 test pattern and figure 7.7 corresponds the measurements from TG18-UNL80 test pattern. As can be seen from the figures, there are huge variations between individual displays.

The uniformity measured from UNL10 test pattern were 10 % or under for 15 displays, over 10 % and equal or below 20 % for 18 displays and over 20 % but under or equal to 30 % for 6 displays. For the uniformity measured from UNL80 test pattern were 10 % or under for 10 displays, over 10 % and equal or below 20 % for 27 displays and over 20 % but under or equal to 30 % for 2 displays. It is notable that all the devices pass the requirement of uniformity being less or equal to 30 %.

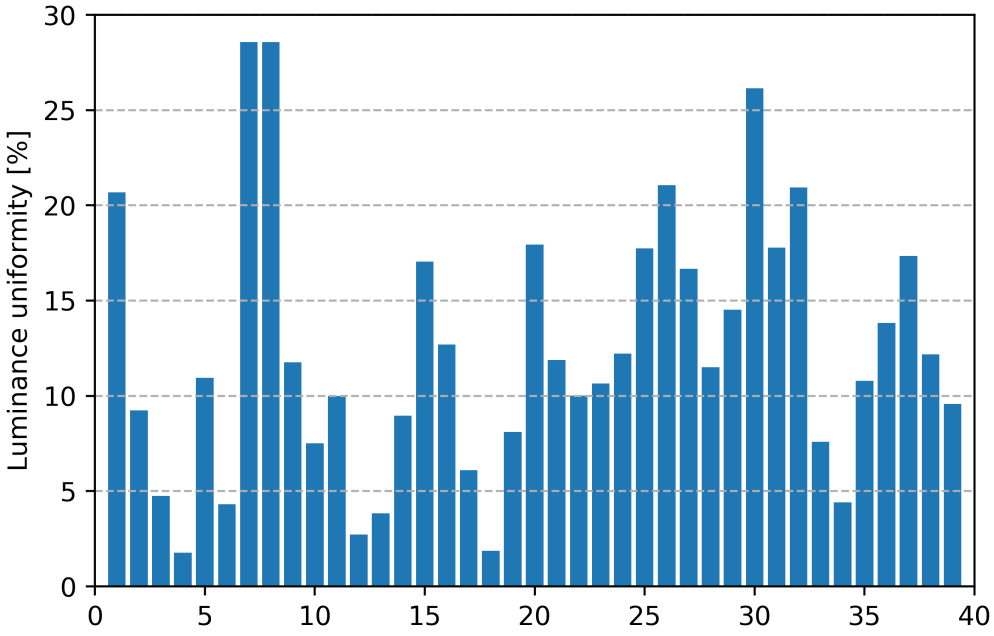

Figure 7.6. *Calculated luminance uniformities from the UNL10 test pattern measurements.*

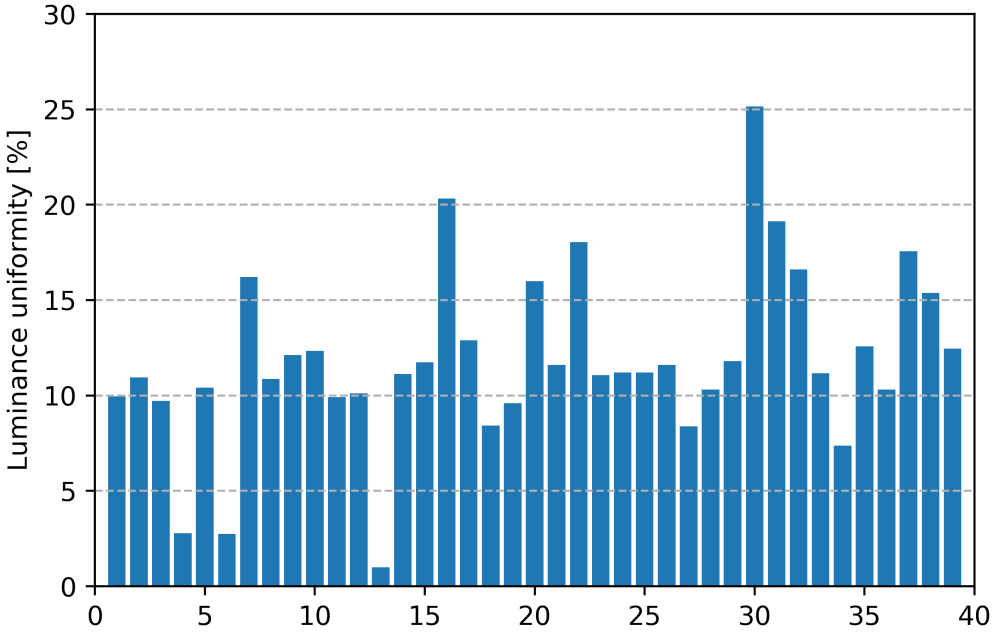

Figure 7.7. *Calculated luminance uniformities from the UNL80 test pattern measurements.*

7.6 Illuminance

As stated before, the measured illuminance values were measured in the average lighting conditions used in examinations. All the high illuminance values (over 50 lux) were measured on devices that are used in angiography operation rooms or in first aid unit. For the majority, in total for 28 displays, the measured illuminance was under 10 lux. For 5 displays the illuminance was between 10 and 20 lux, for one display the illuminance was between 30 and 40 lux and for the rest 5 it was over 100 lux. The maximum was measured to be 221,6 lux. All the measurement results are presented in figure 7.8 and in table A.1.

In most of the rooms there were windows but also blinds and curtains to cover the windows. There were also dimming light switches in many rooms, which enabled the lighting to be adjusted properly. All measurements were done in summer in the middle of the day when the daylight was brightest, so the natural lighting was most of the time quite high. When considering the revised recommendations only few displays were usually operated with lighting level between 25 and 50 lux. However, it must be noted that the ambient lighting was continuously adjustable in most cases and the illuminance level was chosen by the staff performing examinations. So they probably do not experience disruptive eye fatigue which they themselves would notice.

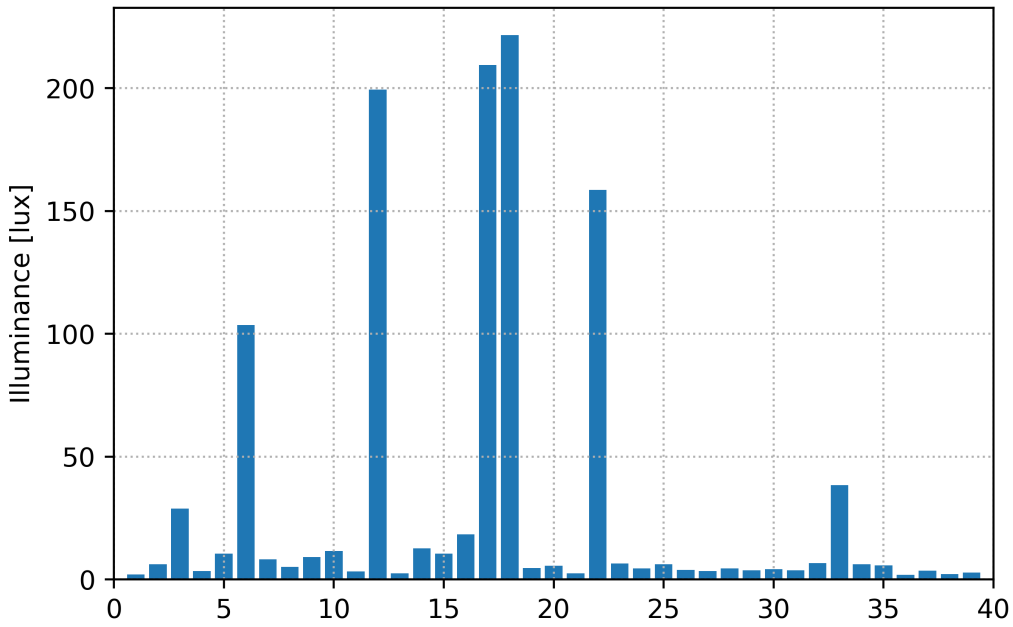

Figure 7.8. *Measured illuminances.*

7.7 Grayscale standard display function

As discussed before, in chapter 6, it was clear that GE's device displays would no be GSDF compliant as they are gamma calibrated and these two are different things. Due to this, the Philips' devices are discussed separately. For all devices the average absolute deviation from GSDF is shown in figure 7.9. To make the visual evaluation easier in all the figures, the 10 % deviation from GSDF is marked with yellow dashed line and 20 % deviation is marked with red dashed line.

When compared later individually to each manufacturer's devices, it can be clearly seen that they must be discussed separately. On average none of the devices are GSDF compliant as the first value deviates from the GSDF over 30 %. In most cases the value was below as can be seen in figures A.2 and A.3.

When measurement point is below the GSDF curve it means that the change in luminance between two subsequent measurement patterns is lower than recommended when it is compared to the change in pixel values, which is constant. Examples of measured luminance responses for singular displays are presented in figures A.1-A.3.

Average absolute deviation was chosen as it is not affected as much by large singular deviations and it might even be considered as a better description than using variance. [15]

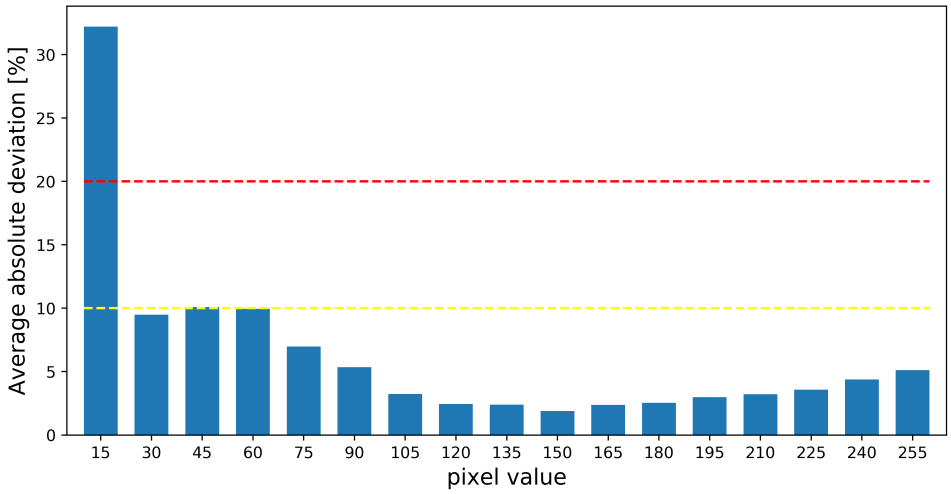

Figure 7.9. *Average absolute deviation from the GSDF for every measured pixel value for every device.*

The average absolute deviation from the GSDF for GE's devices is presented in figure 7.10. On average GE's device displays do not pass the AAPM requirements for GSDF compliance. And also, as can be seen from table A.3, none of the displays are GSDF compliant. This was to be expected as the displays use gamma calibration instead of GSDF.

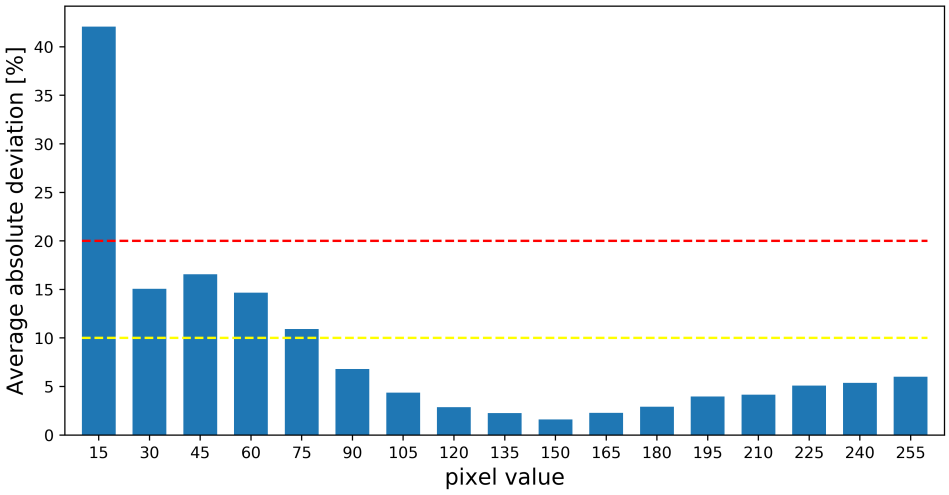

Figure 7.10. *Average absolute deviation from the GSDF for every measured pixel value for GE's devices.*

The average absolute deviation from the GSDF for Philips' devices is presented in figure 7.11. As can be seen, on average the Philips' displays are much closer to GSDF and only one point is above the 20 % limit while all the others are below the recommended 10 %. This however fails most of the displays as can be seen from table A.4. On the other hand, the change in luminance was too small in most cases and it could be modified by increasing the black level of the monitor. As there is possibility to change the settings and enhance the black level, probably most of the displays could be adjusted to be GSDF compliant. In total with the default measurement settings four displays fulfilled the secondary display criteria and two displays fulfilled the primary display criteria for GSDF compliance.

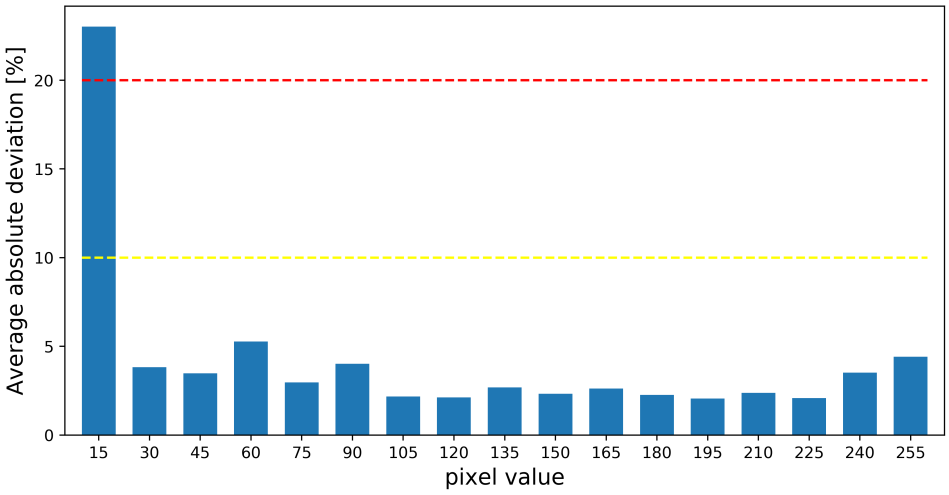

Figure 7.11. *Average absolute deviation from the GSDF for every measured pixel value for Philips' devices.*

7.8 Visual assessment

In the visual assessment TG18-UN(L) test patterns were used to check if there were any dead or faulty pixels. No dead or faulty pixels were observed in any of the displays.

TG18-QC test pattern was used for a quick overall assessment of the display. No distortions or artefacts were observed. The pattern was also used for a quick evaluation of luminance/contrast. A minimum requirement is that the 5 % and 95 % squares should always be visible. This condition was met by all devices when the ambient lighting was minimised, but few devices would probably fail the test in a bit brighter lighting conditions.

Also, the "QUALITY CONTROL" texts were evaluated and a clear difference was noticed between displays which were GSDF compliant or at least close to it. On these displays several grey letters on the black background were observed when compared to displays that were not even close to GSDF. However, anything quantitative about maximum luminance values cannot be said based on how many characters can be observed, as can be seen from figure 7.12. It also should be noted that the observations are of course subjective.

The visual tests should be performed with minimized ambient lighting and in the lighting conditions used in exams. However, as more emphasis was put on the technical performance of the device and not so much on the surrounding environment in this research, the visual evaluations were done only in minimized ambient lighting conditions.

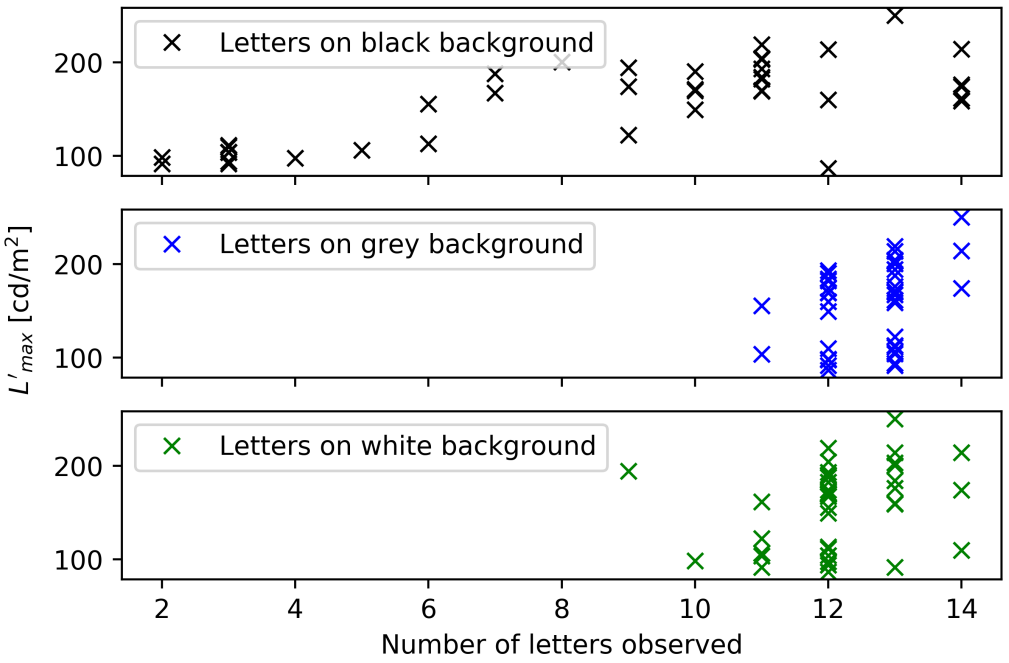

Figure 7.12. *Number of letters observed from "QUALITY CONTROL" text and maximum luminance of the display.*

8. DISCUSSION

The goal of this study was to evaluate the condition of ultrasound imaging device displays used in The Hospital District of South Ostrobothnia and Pirkanmaa Hospital district, and to ponder the possible quality control procedures that should be introduced to hospitals' quality assurance programs.

These kind of quality control procedures are already implemented for x-ray imaging devices and displays used in interpretation of medical images. There have been extensive studies how the display quality affects the diagnostics from digital radiographs but these have all considered only x-ray images [8, 17, 21, 23]. Only few studies have considered ultrasound imaging device displays and the one where ultrasound device displays were discussed more in detail is 7 years old and the methods used in the study were somewhat limited [26, 34].

The most commonly used test patterns and test criteria are from the AAPM TG18 report. And although in the report no imaging modality is considered different from else and they should all be treated equally, these practices have been generally adopted only to x-ray imaging. On the other hand, it is understandable that the requirements are higher when ionizing radiation is used but on the other hand again, with quite small amount of work, the quality of other imaging modalities displays could be followed. If the quality of display could affect diagnostics there are no reasons to ignore the quality assurance of other imaging modality displays.

Measurements could not be carried out as extensively as first was planned as some technical difficulties were encountered. As stated before in chapter 6, the measurements were performed only on some Philips' and GE's device models as other manufacturers' devices did not support the importing/reading of the test patterns from CD or USB flash drive and there were no appropriate test patterns in the internal memory of the device. Philips' devices did not generally support the reading/importing of the test patterns. Fortunately all the required test patterns were found from the devices' hard drives on newer models and also on the older models which software had been updated quite recently. GE's devices had most of the needed test patterns but they were displayed on different part of the screen than the examination image. Due to this it was decided to load all the test patterns from CD. There were also some GE's Voluson models in Seinäjoki in gynaecological and mother outpatient clinics, which did not have the test patterns in internal memory and they did not support the importing/reading of the images from external sources.

The most interesting and notable results are the maximum luminances of the displays. To evaluate how the age affects the maximum luminance, the displays were ordered by

the year of purchase and the result is presented in figure 8.1. From the figure can be approximated, that if the display should fulfil at least the secondary display maximum luminance criteria, the life time of display would be about 5 years. Of course, the operating hours affect the waning of the monitor and the life time could be increased if screen saver options would be brought into use. It was a surprising detail that in the worst cases devices and monitors can be turned on for hours although they are not used and there are no screen saver options.

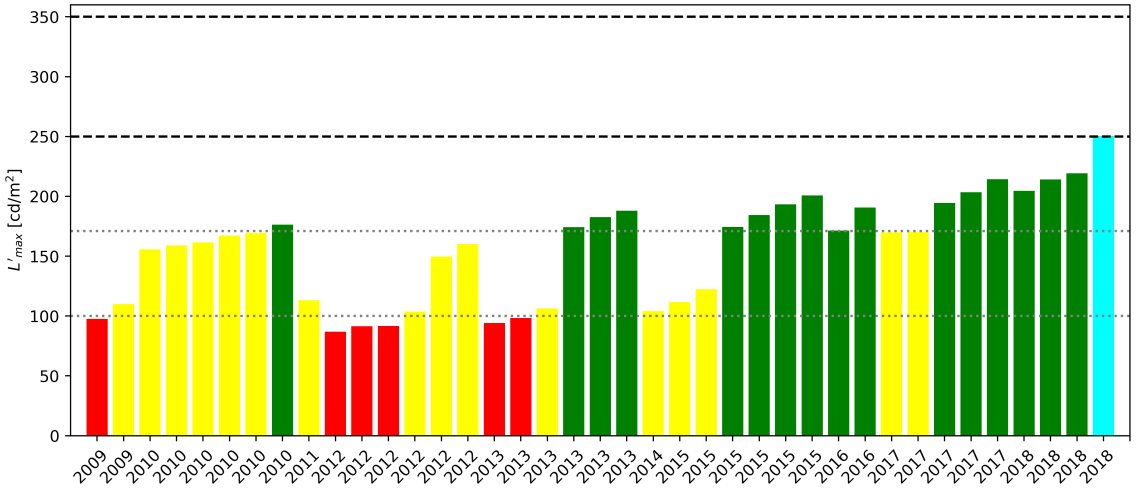

Figure 8.1. *Average absolute deviation from the GSDF for every measured pixel value for Philips' devices.*

Another important thing to address is the greyscale calibration of the device. Only a few displays were GSDF compliant on the measurement settings. On the contrary, as it was possible to change the black level on most of Philips' monitors, many of them could probably be set to follow the GSDF. However, the need for the monitors to be GSDF compliant is uncertain. Although, the GSDF is based on the sensitivity of the human eye, the ultrasound images are very different from x-ray images. They can also be altered while doing the imaging and in general images acquired with ultrasound might be brighter than the x-ray images. As the GSDF enhances the darker part of displaying the greyscales the need for it becomes questionable if the whole image is on average quite bright and no darkest greyscale values are present. Doctors have also become accustomed to the overall brighter images so they might resist the change, especially if it cannot be justified with immediate benefits in diagnostics.

A few things should be addressed about the reliability of the measurement results. The reflected ambient luminance L_{amb} was measured with "free hand" without any support, with the contact luminance meter, from approximately 15 cm away from the display surface. Due to this the light detector might not have been always perfectly perpendicular to the display surface and therefore the best result might not have been acquired. This was attempted to compensate by choosing the maximum value that could be measured, when the detector was approximately perpendicular to the display. Also, related to the ambient

luminance and illuminance, the lighting conditions used were "average conditions" used during examinations and sometimes they were estimated by the measurer, when no other staff was available. It was noted that at least the radiologists and nurses with whom these matters were discussed, were really aware of the effects of high illuminance levels and tried to keep the lighting in low level. However, it is unknown if other doctors who use ultrasound frequently are aware of this.

Another thing related to the reliability of the measurements is the calibration of the Tampere University Hospital's device. It was calibrated last time in 2014. It was discussed if the device should be calibrated at some point but as the measurements were not finished and last time it took many weeks to get the device back when it was sent to be calibrated, so it was decided that the measurements should be finished first. A few displays in Seinäjoki were measured with both devices and as the results were not large it was decided that the performance of the Tampere University Hospital's device was sufficient.

The interest in overall ultrasound quality control has risen but the development will be slow and it will always depend on the physicists and other staff unless national regulations are set. Although, some manufacturers have realised that some instances are interested in the quality control of ultrasound and therefore included the test patterns into their machines it will probably take a while until the displays start to fulfil the AAPM recommended criteria. When considering the hospital side, it does not help that that renewing the displays can cost thousands of euros while the provided displays are still only approximately as good as average laptop or consumer grade displays.

The overall knowledge of manufacturers about the displays in their machines is also quite poor. I contacted both GE's and Philips' representatives and asked them several questions about their displays. After a while I got email from GE and they answered me that they would bill for every hour of work done while contacting their factories and subcontractors and the approximate cost would be approximately from 2500 € to 3000 €. They did not have even basic knowledge about what kind of panels are used in the displays. The Philips representative was a lot more cooperative and he promised to get back to me when he has acquired as many answers as possible (for free).

The next logical step in this would be to study at which point the poor quality of the display starts to affect the diagnostics. Ultrasound imaging is the only modality where the actual imaging is performed by the doctors and they usually interpret the image while examining the patient. This means that the experience of the doctor has huge impact. The quality of the technology has probably a smaller meaning for experienced doctors but when considering new specialising doctors. Good quality displays might help them to make faster and more confident decisions.

9. CONCLUSION

The aim of this study to investigate the technical performance of ultrasound device monitors in the Hospital District of South Ostrobothnia and Pirkanmaa Hospital District. The measurements were performed in several operational units of both hospital districts. Most of the measured devices were located in Seinäjoki Central Hospital and Tampere University Central Hospital. The original plan was to measure all the displays in Seinäjoki and all the displays under radiology department in Tampere but as some technical difficulties rose, only displays from certain manufacturers could be measured. This had a larger effect in Seinäjoki which had a more wider range of devices from different manufacturers.

The measurements were done according to AAPM TG18 report (published in 2005) which discusses the quality control of displays used in medical imaging. The report recommends several tests, quantitative and visual, to be performed for radiological displays. The test patterns used in the assessment were either loaded from CD or found in some machines. Only some of these tests were chosen as the protocol would have been extremely heavy if all the tests were included. Also, some of the tests were designed mainly for CRT displays, while all the displays were LCDs.

The acquired results were compared to the old AAPM TG18 report recommendation values and to newer values revised by AAPM, ACR and SIIM in 2017. In both of these documents there are minimum recommendation values for primary and secondary displays. As was partly expected, many of the displays were not in good condition. The older criteria were mostly considered when analysing results, especially when considering maximum luminance, as not even all the newest devices could fulfil the new recommendations.

There are no studies done with ultrasound imaging that investigate if the quality of the display has effect on diagnostics. This should be studied as the ultrasound images are different from x-ray images. The experience of the examining radiologist should also be considered as ultrasound imaging is the only modality where the doctors perform the imaging and interpret the image at the same time. It is unknown if the DICOM calibration has effect on diagnostics, it should be included in the studies. As ultrasound images are fundamentally different from x-ray images and they can be modified and made generally brighter while imaging, the results might be different.

As the only requirement from Finnish authorities is that the used devices should be "good enough" the responses to the results depends on the physicists and the hospitals. The oldest displays were 9 years old and, almost without exception, displays that were over 4 years old were no way in a sufficient condition. I would recommend that the default change interval of the displays should be 5 years and singular displays could be evaluated

separately if not changed.

As for recommendation for quality control measurements for hospitals: the maximum luminance should be measured biannually or annually and the lighting conditions in the examination rooms should be always taken into consideration, although they were on appropriate level in most places. These measurements are easy to perform, as the test patterns can be found from most of the machines, and they do not take much time so they should be included in the quality control program of ultrasound imaging devices.

Additionally, when the hospitals are purchasing new equipment the absolute minimum requirements for technical performance of the device display should be the revised secondary display criteria presented in table 9.1. [27] The GSDF compliance could be flexible as no studies have been done with ultrasound imaging. This would ensure the high quality of diagnostics in the future and save a lot of trouble if Finnish authorities decide to do something about this matter. It would also be consistent and logical that all the imaging modalities would have same requirements.

Table 9.1. *Recommended minimum requirements for technical performance of ultrasound imaging device displays. [27]*

L_{max} [cd/m^2]	L_{min} [cd/m^2]	*CR*	Luminance uniformity [%]	GSDF compliance
250	0,8	>250	$\leq$ 30	$\leq$ 20 %

REFERENCES

[1] American Association of Physicist in Medicine Homepage. Available (accessed on 24.7.2018): https://www.aapm.org/

[2] American Association of Physicists in Medicine, Task Group No. 270 - Display QA (TG270). Available (accessed on 11.9.2018): https://www.aapm.org/org/structure/?committee{_}code=TG270

[3] American Association of Physicists in Medicine, Task Group No. 316 - Ultrasound Modality-Specific Display Presentation Consistency (TG316). Available (accessed on 11.9.2018): https://www.aapm.org/org/structure/?committee{_}code=TG316

[4] American Association of Physicists in Medicine, Assessment of display performance for medical imaging systems, Med Phys, Iss. 03, 2005, pp. 1–156.

[5] N.B. Bevins, Display Quality Assurance: Recommendations from AAPM TG270 for Tests, Tools, Patterns, and Performance Criteria. Available: http://amos3.aapm.org/abstracts/pdf/127-38283-418554-126069-1406870884.pdf

[6] W. den Boer, Active Matrix Liquid Crystal Display: Fundamentals and Applications, 2005.

[7] P.C. Brennan, M. McEntee, M. Evanoff, P. Phillips, W.T. O'Connor, D.J. Manning, Ambient lighting: effect of illumination on soft-copy viewing of radiographs of the wrist., AJR. Am. J. Roentgenol., Vol. 188, Iss. 2, 2007, pp. 177–180.

[8] A. Butt, M. Mahoney, N.W. Savage, The impact of computer display performance on the quality of digital radiographs: A review, Aust. Dent. J., Vol. 57, 2012, pp. 16–23.

[9] K. Chakrabarti, R.V. Kaczmarek, J.A. Thomas, A. Romanyukha, Effect of room illuminance on monitor black level luminance and monitor calibration, J. Digit. Imaging, Vol. 16, Iss. 4, 2003, pp. 350–355.

[10] J. Chen, W. Cranton, M. Fihn, Handbook of visual display technology, Handb. Vis. Disp. Technol., Vol. 1-4, 2012, pp. 1–2694.

[11] CIE, Fundamental chromaticity diagram with physiological axes Parts 1 and 2. Technical Report 170-1, 2006.

[12] CIE Proceedings, Vol. 1, Sec 4, 1951, p. 37.

[13] J. Cross, Three-Minute Tech: AMOLED, 2012. Available (accessed on 12.11.2018): https://www.pcworld.com/article/2000075/three-minute-tech-amoled.html

[14] J.M. Goo, J.Y. Choi, J.G. Im, H.J. Lee, M.J. Chung, D. Han, S.H. Park, J.H. Kim, S.H. Nam, Effect of Monitor Luminance and Ambient Light on Observer Performance in Soft-Copy Reading of Digital Chest Radiographs, Radiology, Vol. 232, Iss. 3, 2004, pp. 762–766.

[15] S. Gorard, Revisiting a 90-Year-Old Debate: The Advantages of the Mean Deviation, Br. J. Educ. Stud., Vol. 53, Iss. 4, 2005, pp. 417–430.

[16] J. Gurski, L.M. Quach, Display Technology Overview, Lytica White Pap., 2005, pp. 1–23.

[17] M.H. Hameed, F. Umer, F.R. Khan, S. Pirani, M. Yusuf, Assessment of the diagnostic quality of the digital display monitors at the dental clinics of a university hospital, Informatics Med. Unlocked, Vol. 11, Iss. January, 2018, pp. 83–86.

[18] H. Hong, H. Shin, I. Chung, In-plane switching technology for liquid crystal display television, IEEE/OSA J. Disp. Technol., Vol. 3, Iss. 4, 2007, pp. 361–370.

[19] V. Järvinen, M. Kaivola, A. Ojanperä, M. Tala, T. Tarkkonen, Kyselytutkimus toiminnanharjoittajille säteilylainsäädännön uudistustarpeista, 2015. Available: http://urn.fi/URN:ISBN:978-952-309-268-6

[20] R.A.L. Jones, Soft Condensed Matter, 1st ed., Oxford University Press, New York, 2002, pp. 102–117.

[21] S. Kallio-Pulkkinen, S. Huumonen, M. Haapea, E. Liukkonen, A. Sipola, O. Tervonen, M.T. Nieminen, Effect of display type, DICOM calibration and room illuminance in bitewing radiographs, Dentomaxillofacial Radiol., Vol. 45, Iss. 1, 2015, pp. 1–8.

[22] M. Koden, OLED displays and lighting, J. Wiley & Sons, Chichester, 2017.

[23] E. Liukkonen, A. Jartti, M. Haapea, H. Oikarinen, L. Ahvenjärvi, S. Mattila, T. Nevala, K. Palosaari, M. Perhomaa, M.T. Nieminen, Effect of display type and room illuminance in chest radiographs, 2016.

[24] M. Matsuyama, J. Morishita, H. Akamine, S. Tokurei, H. Yabuuchi, Y. Nakamura, N. Hashimoto, M. Ohki, Effect of ambient lighting on liquid-crystal displays with different types of surface treatment, Radiol. Phys. Technol., Vol. 6, Iss. 1, 2013, pp. 121–129.

[25] W.R. Mccluney, W. Ross, Introduction to Radiometry and Photometry, 1st ed., Artech House, 1994.

[26] S.C. Moore, C.R. Munnings, D.S. Brettle, J.A. Evans, Assessment of Ultrasound Monitor Image Display Performance, Ultrasound Med. Biol., Vol. 37, Iss. 6, 2011, pp. 971–989.

[27] J.T. Norweck, J.A. Seibert, K.P. Andriole, D.A. Clunie, B.H. Curran, M.J. Flynn, E. Krupinski, R.P. Lieto, D.J. Peck, T.A. Mian, M. Wyatt, ACR-AAPM-SIIM technical standard for electronic practice of medical imaging, 2013. Available: https://cdn.ymaws.com/siim.org/resource/resmgr/guidelines/elec-practice-medimag-2017.pdf

[28] W.Y. Park, A. Phadke, N. Shah, Efficiency improvement opportunities for televisions in India: implications for market transformation programs, Energy Effic., Vol. 7, Iss. 5, 2014, pp. 811–832.

[29] B.J. Pollard, E. Samei, A.S. Chawla, C. Beam, L.E. Heyneman, L.M.H. Koweek, S. Martinez-Jimenez, L. Washington, N. Hashimoto, H.P. McAdams, The Effects of Ambient Lighting in Chest Radiology Reading Rooms, J. Digit. Imaging, Vol. 25, Iss. 4, 2012, pp. 520–526.

[30] H. Roehrig, Displays for Medical Imaging: Physical Characterization & Image Quality. Available (accessed on 12.11.2018): https://siim.org/page/displays{_}chapter2

[31] S. Rosslyn, Digital Imaging and Communications in Medicine (DICOM) Part 14 : Grayscale Standard Display Function, 2004. Available: http://www.ncbi.nlm.nih.gov/pubmed/2188123

[32] S. Rosslyn, Digital Imaging and Communications in Medicine (DICOM) Part 1: Introduction and Overview, Access, Vol. 11, 2004, pp. 1–21.

[33] S. Rosslyn, Digital Imaging and Communications in Medicine (DICOM) Part 14: Grayscale Standard Display Function, Medicine (Baltimore)., Vol. 10, Iss. S1, 2004, pp. 3–4.

[34] M.S. Silosky, R.M. Marsh, A.L. Scherzinger, Imaging acquisition display performance: An evaluation and discussion of performance metrics and procedures, J. Appl. Clin. Med. Phys., Vol. 17, Iss. 4, 2016, pp. 334–341.

[35] STUK, ST Guide 3.3: X-ray examinations in health care, 2008. Available: https://www.stuklex.fi/en/ohje/ST3-3

[36] STUK, Terveydenhuollon röntgenlaitteiden laadunvalvontaopas, 2008. Available: http://urn.fi/URN:ISBN978-952-478-322-4

[37] STUK, Mammografialaitteiden laadunvalvontaopas, 2014. Available: http://urn.fi/URN:ISBN978-952-309-030-9

[38] STUK, Säteily terveydenhuollossa: Röntgentutkimukset, 2015. Available (accessed on 13.11.2018): https://www.stuk.fi/aiheet/sateily-terveydenhuollossa/rontgentutkimukset

[39] STUK, Säteily terveydenhuollossa: Ultraäänitutkimus, 2015. Available (accessed on 13.11.2018): https://www.stuk.fi/aiheet/sateily-terveydenhuollossa/ultraaanitutkimus

[40] The Colour & Vision Research laboratory, University College London - Luminosity functions. Available (accessed on 24.7.2018): http://www.cvrl.org/lumindex.htm

APPENDIX A: MEASUREMENTS AND RESULTS

***Table A.1**. Measurement results.*

Device	**Year**	**L_{max}** [cd/m^2]	**L_{min}** [cd/m^2]	**L_{amb}** [cd/m^2]	**LR'/CR**	**E** [lux]
1	2014	104,0	0,19	0,02	495 / 547	1,95
2	2011	113,2	0,17	0,06	492 / 666	6,13
3	2013	105,9	0,16	0,49	164 / 662	28,87
4	2013	94,15	0,14	0,04	523 / 673	3,45
5	2010	155,6	0,24	0,12	433 / 648	10,54
6	2010	165,6	0,23	1,58	92 / 720	103,6
7	2009	97,52	0,18	0,05	424 / 542	8,23
8	2009	109,8	0,22	0,06	392 / 499	5,09
9	2017	194,1	0,27	0,42	282 / 719	9,1
10	2012	91,49	0,15	0,15	305 / 610	11,51
11	2015	111,6	0,15	0,03	620 / 744	3,30
12	2018	216,1	0,29	3,21	63 / 745	199,4
13	2018	250,3	0,27	0,02	863 / 927	2,49
14	2013	98,28	0,21	0,09	328 / 468	12,64
15	2012	103,6	0,20	0,08	370 / 518	10,41
16	2012	91,35	0,14	0,14	327 / 653	18,41
17	2017	210,5	0,20	3,80	54 / 1053	209,4
18	2017	199,5	0,29	3,94	48 / 688	221,6
19	2015	200,6	0,20	0,06	772 / 1003	4,65
20	2015	122,3	0,20	0,04	510 / 612	5,52
21	2013	187,8	0,23	0,09	587 / 817	2,43
22	2015	182,3	0,17	2,04	83 / 1072	158,5
23	2016	190,5	0,17	0,04	907 / 1121	6,52
24	2017	170,1	0,19	0,02	810 / 895	4,40
25	2017	169,7	0,18	0,06	707 / 943	6,14
26	2013	174,1	0,15	0,04	917 / 1161	3,81
27	2018	214,1	0,15	0,02	1260/1427	3,35
28	2018	204,5	0,21	0,03	852 / 974	4,51
29	2015	193,2	0,14	0,03	1137/1380	3,77
30	2013	182,5	0,18	0,03	869 / 1014	4,16
31	2016	171,4	0,15	0,02	1008/1143	3,67
32	2015	174,3	0,16	0,10	671 / 1089	6,61
33	2012	149,0	0,68	0,63	114 / 219	38,42
34	2010	168,5	0,67	0,73	121 / 251	6,13
35	2012	86,74	0,88	0,06	92 / 99	5,67
36	2012	160,0	1,60	0,05	97 / 100	1,90
37	2010	159,0	1,13	0,03	137 / 141	3,47
38	2010	176,3	1,06	0,03	162 / 166	2,20
39	2010	161,5	1,06	0,04	147 / 152	2,71

***Table A.2**. Luminance uniformities for both test patterns: UNL10 and UNL80.*

Device	**UNL10** (%)	**UNL80** (%)
1	20,69	9,96
2	9,23	10,94
3	4,74	9,71
4	1,77	2,77
5	10,95	10,41
6	4,31	2,75
7	28,57	16,21
8	28,57	10,87
9	11,76	12,12
10	7,52	12,34
11	10,00	9,91
12	2,71	10,11
13	3,84	0,99
14	8,96	11,12
15	17,05	11,74
16	12,70	20,32
17	6,11	12,89
18	1,86	8,43
19	8,11	9,61
20	17,93	15,99
21	11,88	11,60
22	10,01	18,04
23	10,64	11,06
24	12,22	11,21
25	17,74	11,21
26	21,05	11,59
27	16,67	8,38
28	11,49	10,32
29	14,53	11,81
30	26,14	25,15
31	17,78	19,14
32	20,94	16,61
33	7,58	11,17
34	4,41	7,38
35	10,8	12,58
36	13,83	10,31
37	17,34	17,56
38	12,18	15,38
39	9,57	12,45

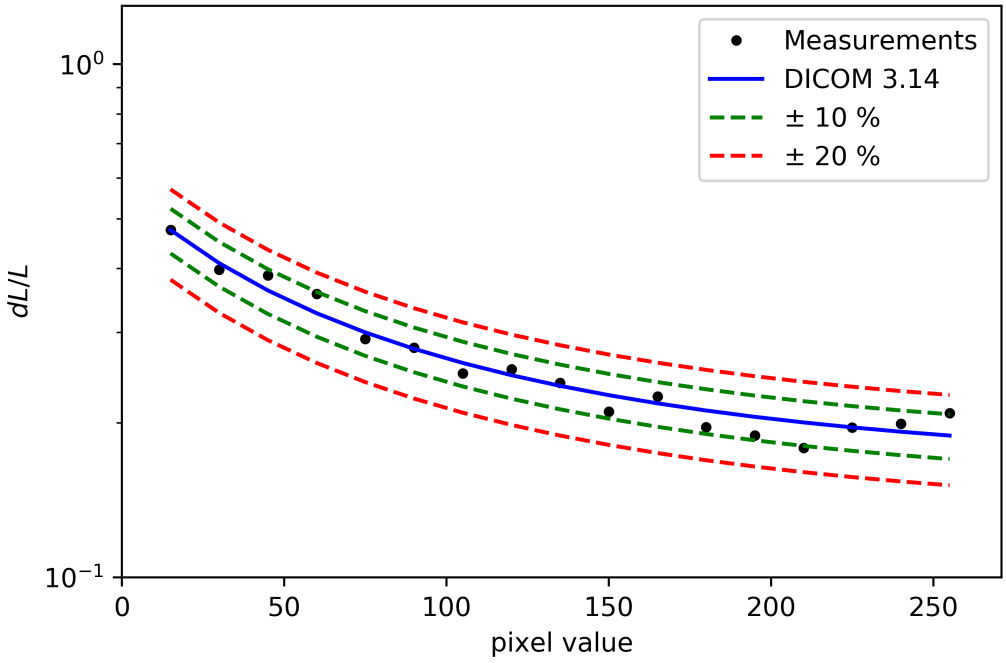

Figure A.1. *Luminance response curve of display with minimum total deviation. Also, one of the two devices (device 36) that are classified as primary.*

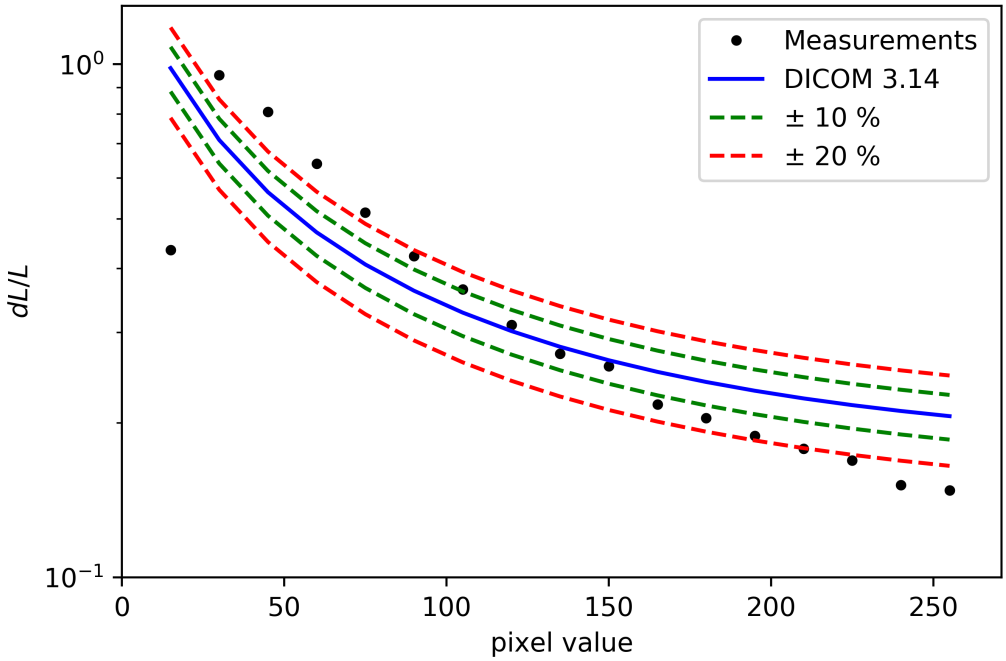

Figure A.2. *Luminance response curve of display with maximum total deviation (device 11).*

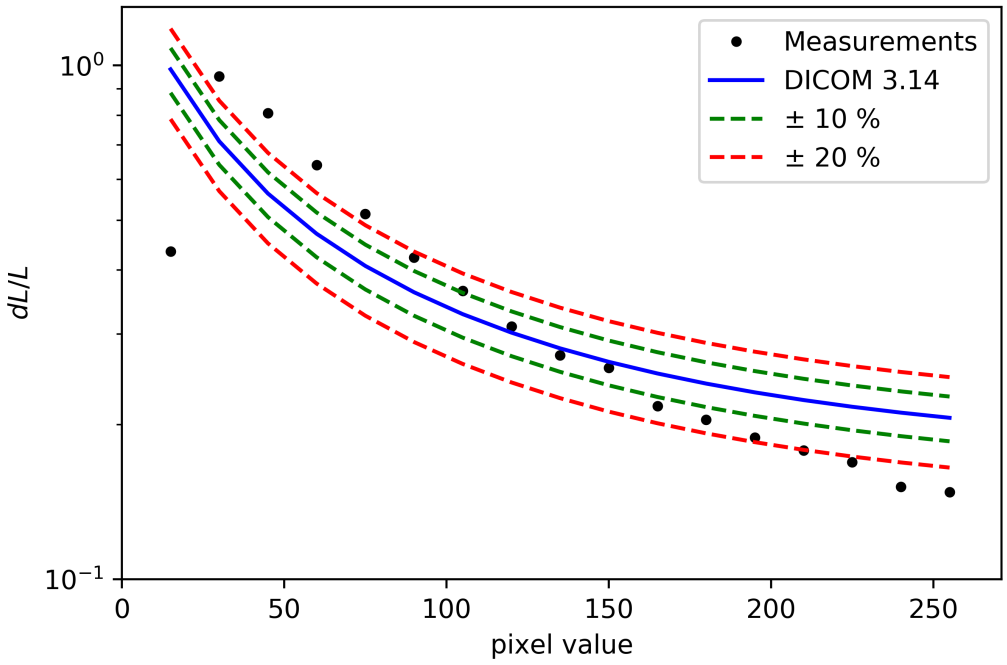

Figure A.3. *Luminance response curve of display with maximum singular point deviation from the GSDF curve (device 15).*

Table A.3. *Results of evaluation for GE's display. First based on the older AAPM TG18 criteria [4] and second based on the revised criteria [27]. Possible options: Primary, Secondary, Pass and Fail.*

Device	Year	L'_{max}	L'_{min}	L_{amb}	LR'	Luminance uniformity	GSDF compliance	Total
1	2014	Secondary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
2	2011	Secondary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
3	2013	Secondary / Fail	- / Fail	Fail / Fail	Secondary / Fail	Pass	Fail	Fail / Fail
4	2013	Fail / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
5	2010	Secondary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
6	2010	Secondary / Fail	- / Primary	Fail / Fail	Fail / Fail	Pass	Fail	Fail / Fail
7	2009	Fail / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
8	2009	Secondary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
9	2017	Primary / Fail	- / Fail	Fail / Pass	Primary / Secondary	Pass	Fail	Fail / Fail
10	2012	Fail / Fail	- / Fail	Fail / Pass	Primary / Secondary	Pass	Fail	Fail / Fail
11	2015	Secondary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
12	2018	Primary / Fail	- / Primary	Fail / Fail	Fail / Fail	Pass	Fail	Fail / Fail
13	2018	Primary / Secondary	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
14	2013	Fail / Fail	- / Fail	Pass / Fail	Primary / Secondary	Pass	Fail	Fail / Fail
15	2012	Secondary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
16	2012	Fail / Fail	- / Fail	Pass / Pass	Primary / Secondary	Pass	Fail	Fail / Fail
17	2017	Primary / Fail	- / Primary	Fail / Fail	Fail / Fail	Pass	Fail	Fail / Fail
18	2017	Primary / Fail	- / Primary	Fail / Fail	Fail / Fail	Pass	Fail	Fail / Fail
19	2015	Primary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
20	2015	Secondary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
21	2013	Primary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail

***Table A.4**. Results of evaluation for Philips' display. First based on the older AAPM TG18 criteria [4] and second based on the revised criteria [27]. Possible options: Primary, Secondary, Pass and Fail.*

Device	Year	L'_{max}	L'_{min}	L_{amb}	LR'	Luminance uniformity	GSDF compliance	Total
22	2015	Primary / Fail	- / Primary	Fail / Fail	Fail / Fail	Pass	Secondary	Fail / Fail
23	2016	Primary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
24	2017	Secondary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
25	2017	Secondary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Secondary	Secondary / Fail
26	2013	Primary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
27	2018	Primary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
28	2018	Primary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
29	2015	Primary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
30	2013	Primary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
31	2016	Primary / Fail	- / Fail	Pass / Pass	Primary / Primary	Pass	Fail	Fail / Fail
32	2015	Primary / Fail	- / Fail	Pass / Fail	Primary / Primary	Pass	Fail	Fail / Fail
33	2012	Secondary / Fail	- / Primary	Fail / Pass	Secondary / Fail	Pass	Secondary	Fail / Fail
34	2010	Secondary / Fail	- / Primary	Fail / Pass	Secondary / Fail	Pass	Secondary	Fail / Fail
35	2012	Fail / Fail	- / Secondary	Pass / Pass	Fail / Fail	Pass	Primary	Fail / Fail
36	2012	Secondary / Fail	- / Primary	Pass / Pass	Fail / Fail	Pass	Primary	Fail / Fail
37	2010	Secondary / Fail	- / Primary	Pass / Pass	Secondary / Fail	Pass	Fail	Fail / Fail
38	2010	Primary / Fail	- / Primary	Pass / Pass	Secondary / Fail	Pass	Fail	Fail / Fail
39	2010	Secondary / Fail	- / Primary	Pass / Pass	Secondary / Fail	Pass	Fail	Fail / Fail